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BODY WAVE MAGNITUDE AND SOURCE MECHANISM

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By

H. S. Jarosch
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BODY WAVE MAGNITUDE AND SOURCE MECHANISM

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ABSTRACT

A new method is proposed for improving the body-wave magnitude determination by using the observed values of the body-wave magnitude (m_b) together with the first motion directions, to obtain by least squares analysis the best double couple source parameters; the resulting radiation pattern is then integrated spatially to provide a corrected estimate of the magnitude. Results for a number of events previously studied by other investigators are presented.

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INTRODUCTION

The body-wave magnitude of an earthquake was defined by Gutenberg and Richter as

$$m_b = \log_{10} A/T + Q - 3$$

where

A is the P-wave amplitude in millimicrons

T is the period in seconds

Q is the Gutenberg-Richter (1956) distance-depth correction.

This magnitude of course, depends on the amplitude recorded at a particular station observing the earthquake. For want of a better method, the arithmetic mean of individual station magnitudes was chosen to be representative of the true body-wave magnitude. This would be correct if the source were assumed to be purely compressional (azimuthally uniform).

However, our knowledge of source mechanisms has increased to a point where it is now known that the mechanism of most earthquakes may be well represented by a double couple source mechanism, Stauder and Bollinger (1964). This, in turn, implies that the body-wave radiation pattern is not azimuthally uniform. If we want to be still more accurate, we can also include the effect of a moving source. In any case, the arithmetic mean of the observations does not represent the mean of a radiation pattern caused by a fixed or moving double couple. Hence it is desirable to find a better way of defining the "true" body-wave magnitude.

We propose that a better measure of the "true" body-wave magnitude may be obtained by taking the amplitude of a purely compressional source whose radiation pattern has the same area as the observed radiation pattern.

Naturally, this means that we have to know the source parameters, i.e., the dip direction, dip angle and slip angle of the fault plane and the auxiliary plane.

In order to find the source parameters, two totally different methods have been used to date. The first is a purely geometrical approach, using only the directions of the first motion of P-waves. More recently the study of the polarization angle of the S-wave has further helped to improve estimation of the source parameters. However, as Stauder and Nuttli (1965) point out:

> "Examination of multiple solutions, i.e., by several different authors for one and the same earthquake, as also a comparison of groups of fault plane solutions for a given region evidense poor agreement and systematic differences in solutions by different authors. This evidence requires that caution should be exercised in drawing conclusions from the existing accumulation of published fault plane solutions."

Although some of the directions of the first motions of the P-waves are reported, no data are readily available on polarization angles, and hence a detailed visual study of the seismograms is necessary for the analysis of source parameters using the above method.

The second method which has been used is spectral equalization. This is applicable to both body and surface waves and source parameters may be obtained, but with this method it is necessary to use digitized seismograms of a worldwide network, which are not readily available.

The method which we propose here consists of using data which are readily available, i.e., reported first motion directions together with observed body-wave magnitudes as given by the C&GS Earthquake Data Reports and the ISC Bulletin.

Of course, the method is bound to be inaccurate if there are large gaps in the azimuthal coverage, but in this case the other methods also fail. It is hoped that for earthquakes of magnitude 5 and larger, an approximate solution of the source parameters may be obtained and hence a better value of the mean body-wave magnitude may be established.

METHOD

The method is based on a number of assumptions:

1. Using only WWNSS stations, it is not necessary to make instrumental corrections since the m_b is computed on the basis of A/T and the instrument responses are nearly identical.

2. Geometrical spreading is accounted for by the Gutenberg-Richter correction for distance and depth of focus.

3. The major contribution to the difference in the observed variation of m_b with azimuth is caused by the source radiation pattern.

4. A double-couple source accounts for the radiation pattern.

5. Sufficient azimuthal coverage exists in the observations to allow reasonably unambiguous determination of the source mechanism.

This method is not intended to replace the body-wave equalization procedure as given by Ben Menahem, et al (1965). It is intended to provide a small correction to the mean m_b.

The model taken is the linear regression with zero intercept

$$B_i = KA_i + e_i$$

where B_i is the observed amplitude ($B_i = 10^{M_i}$)

K is a constant to be determined

A_i is the calculated amplitude (as given by Ben Menahem et al (1965)

e is the error in the ith observation.

The calculated amplitude at the i'th station is related to the source parameters by:

$$A_i = a_o + a_1 \sin(\theta - \theta_o) + a_2 \sin 2(\theta - \theta_o) + b_1 \cos(\theta - \theta_o) + b_2 \cos 2(\theta - \theta_o)$$

where

$$a_o = 1/4 \sin\lambda \sin 2\delta\,(3\cos^2 i_h - 1)$$

$$a_1 = 1/2 \sin\lambda \cos 2\delta \sin 2i_h$$

$$b_1 = 1/2 \cos\lambda \cos\delta \sin 2i_h$$

$$a_2 = -1/2 \cos\lambda \sin\delta \sin 2i_h$$

$$b_2 = 1/4 \sin\lambda \sin 2\delta \sin 2i_h$$

θ is the azimuth (east of north) of the station as seen from the epicenter

θ_o is the azimuth (east of north) of the strike direction of the assumed fault plane.

δ is the dip angle

λ is the slip angle

i_h is the take-off angle

Figure 22 shows the geometry of the source parameters.

We wish to use a least squares procedure to determine the source parameters. To do this, we minimize the sum of the squares of the errors, i.e., we choose $\hat{K}$ so that

$$E = \sum e_i^2 = \sum (B_i - KA_i)^2 \text{ is minimized.}$$

Hence the estimated value for K is given by

$$\hat{K} = \frac{\sum B_i A_i}{\sum A_i^2}$$

Since $A_i(\lambda) = -A_i(\lambda+180°)$ we determine which half-plane has the smaller error, by choosing

$$\hat{K} = \frac{\left|\sum B_i A_i\right|}{\sum A_i^2}$$

and then $e_i = \begin{cases} B_i - \hat{K}A_i & \text{for } 0° \leq \lambda < 180° \\ B_i + \hat{K}A_i & 180° \leq \lambda < 360° \end{cases}$

Only stations for which we have values of m_b were used in the estimation of $\hat{K}$. In order to include also stations for which m_b is not given, but the first motion direction is given, we assumed an observed value whose absolute value was that of the calculated value and whose sign was the sign of the observed first motion, i.e.,

$$B_i = \text{sign}\ (STA_i)\ \hat{K}|A_i|$$

so that the contribution $e_i = 0$ if the signs of the observed and calculated values were the same and $2\hat{K}|A_i|$ if the signs were opposite. This helps to insure that the sign of the larger amplitudes will cause a larger error, if they are different from the observed.

In order to calculate the mean m_b, it is first necessary to define a mean amplitude for a radiation pattern. We intend to use as a mean amplitude the amplitude of a purely compressional (azimuthally uniform) source whose radiation pattern has the same area as the observed radiation pattern:

$$\pi\bar{A}_i^2 = 1/2 \int_0^{2\pi} A_i^2\ (\theta)d\theta.$$

This leads to

$$\bar{A}_i = \{\frac{1}{\pi}[a_o^2 + 1/2\,(a_1^2 + a_2^2 + b_1^2 + b_2^2)]\}^{1/2}$$

Now since the coefficients a_o, a_1, a_2, b_1 and b_2 are functions of the take-off angle i_h (which is different for each station), we simply compute an arithmetic mean of the means $\bar{A}_i$, so that finally the mean amplitude is given by

$$\bar{A} = \frac{\hat{K}}{N} \sum_{i=1}^{N} \bar{A}_i$$

and hence the mean m_b is given by

$$\bar{M} = \log_{10} \bar{A}.$$

We have thus calculated a new mean value of m_b which has been corrected for the radiation pattern. The standard error of estimation of the corrected m_b can be calculated from the t-distribution. Arbitrarily taking our confidence limits at 90%, we find

$$\hat{K}_+ = \hat{K} + \frac{t_{.95}^{N-1}\, S}{(\sum_{i=1}^{N} A_i^2)^{1/2}}$$

$$\hat{K}_- = \hat{K} - \frac{t_{.95}^{N-1}\, S}{(\sum_{i=1}^{N} A_i^2)^{1/2}}$$

where $S^2 =$

$$\frac{1}{N-1}\sum_{i=1}^{N}(B_i - \hat{K}A_i)^2 = \frac{1}{N-1}\sum_{i=1}^{N}\hat{\ell}_i^{\,2}$$

$t^{N-1}_{.95}$ is the value of the student's t-distribution at the 95% confidence limit, for n-1 degrees of freedom.

Hence the upper and lower confidence limit for the body wave magnitude is found from

$$\overline{M}_+ = \log_{10} \overline{A}_+$$

$$\overline{M}_- = \log_{10} \overline{A}_-$$

where $\overline{A}_+ = \frac{\hat{K}_+}{N} \sum_{i=1}^{N} \overline{A}_i$

$$\overline{A}_- = \frac{\hat{K}_-}{N} \sum_{i=1}^{N} \overline{A}_i$$

These values are shown in Table 1.

Algorithm for Obtaining Source Parameters

The initial strike angle, step size and number of steps are given as input parameters. A coarse mesh search is carried out to find the best strike angle and dip and slip angles. The step size for the dip and slip angles is taken to be 10°.

A fine mesh search is then carried out keeping the strike angle found in the first stage fixed and varying the dip and slip angles to find the least squares fit, in steps of 1°. Details are given in the flow chart in the appendix to this report.

AMBIGUITY OF RESULTS

When one finds a fault-plane solution using first motions only, there exists an ambiguity in the result, in that it is not possible to decide which is the fault plane and which is the auxiliary plane. Similarly, using the radiation pattern, Ben Menahem et al., (1965) found the amplitudes and directions of compressional, SV and SH radiation to be:

$$\vec{U}_p = \left\{ \frac{L_o ds}{2\pi v_p} \left(\frac{v_s}{v_p} \right)^2 \right\} (\vec{a}\cdot\vec{R})\ (\vec{n}\cdot\vec{R})\ \vec{R}$$

$$\vec{U}_{sv} = \left\{ \frac{L_o ds}{4\pi v_s} \right\} \left[(\vec{n}\cdot\vec{R})\ (\vec{a}\cdot\vec{\Phi}) + (\vec{a}\cdot\vec{R})\ (\vec{n}\cdot\vec{\phi}) \right] \vec{\Phi}$$

$$\vec{U}_{sH} = \left\{ \frac{L_o ds}{4\pi v_s} \right\} \left[(\vec{n}\cdot\vec{R})\ (\vec{a}\cdot\vec{\theta}) + (\vec{a}\cdot\vec{R})\ (\vec{n}\cdot\vec{\theta}) \right] \vec{\theta}$$

where

$\vec{a}$ is the vector in the direction of motion

$\vec{n}$ is the vector normal to the fault plane.

Since the vector $\vec{a}$, the direction of motion, is normal to the auxiliary plane and $\vec{n}$ is the vector normal to the fault plane, it can be seen that the radiation pattern is unchanged by the interchange of $\vec{a}$ and $\vec{n}$; thus the same ambiguity which exists for the fault-plane solution, also exists for the radiation pattern method.

Second Solution of the Fault Plane

In the previous section we explained that in finding a solution of the source parameters, there exists another solution, whose radiation pattern is identical with that

already found. Hence, since we do not know which is the fault plane and which is the auxiliary plane, it is necessary to compute also the second solution. By comparing the mechanisms of groups of earthquakes from the same area having similar depth of focus, we might be able to see that one of the planes is similar in all cases in order to decide that this is the fault plane, assuming that the source mechanism does not change greatly.

It is assumed that one solution of θ_o, δ and λ has been found already. In Ben Menahem et al (1965) the three coordinate axes are taken in the strike direction (x_1), a direction opposite to the horizontal projection of the dip direction (x_2) and vertically upwards (x_3).

Making a transformation so that we have x_1' pointing North, x_2' West and x_3' vertically upwards for a righthand system, we can describe the transformation of the unit vectors by the matrix relation:

$$\begin{bmatrix} \vec{e}_1 \\ \vec{e}_2 \\ \vec{e}_3 \end{bmatrix} = \begin{bmatrix} \cos\theta_o & \sin\theta_o & 0 \\ -\sin\theta_o & \cos\theta_o & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \vec{e}_1' \\ \vec{e}_2' \\ \vec{e}_3' \end{bmatrix}$$

where θ_o is the strike angle measured clockwise from North.

Hence we can describe the direction of motion, the "null" vector and the vector perpendicular to the direction of motion

by the matrix relation

$$\begin{array}{c} \vec{a} \\ \vec{b} \\ \vec{n} \end{array} = \begin{array}{cccc} \cos\lambda\cos\theta_o - \sin\lambda\cos\delta\sin\theta_o & \cos\lambda\sin\theta_o + \sin\lambda\cos\delta\cos\theta_o & \sin\lambda\sin\delta & \vec{e}_1' \\ \sin\lambda\cos\theta_o - \cos\lambda\cos\delta\sin\theta & \sin\lambda\sin\theta_o + \cos\lambda\cos\delta\cos\theta & \cos\lambda\sin\delta & \vec{e}_2' \\ \sin\delta\sin\theta_o & -\sin\delta\cos\theta_o & \cos\delta & \vec{e}_3' \end{array} \quad (2)$$

The vector $\vec{a}$ lies in the fault plane in the direction of motion and hence its direction cosines are the direction cosines of the auxiliary plane, which is normal to the fault plane. The vector $\vec{n}$ is normal to the fault plane and hence its direction cosines are the direction cosines of the fault plane. The vector $\vec{b}$ lies in the fault plane normal to the direction of motion and hence it is the "null" vector, the intersection of the fault

plane and the auxiliary plane.

These relations are needed to compute the slip angles, assuming that each plane in turn represents the fault plane.

Given one solution of the source parameters θ_1, δ_1, λ_1 we wish to find the second solution θ_2, δ_2, λ_2. We can do this by remembering that $\vec{a}_1$ and $\vec{n}_1$ of one solution become $\vec{n}_2$ and $\vec{a}_2$ of the other solution and hence by equating direction cosines, we have

$$\cos \lambda_1 \cos \theta_1 + \sin \lambda_1 \cos \delta_1 \sin \theta_1 = - \sin \delta_2 \sin \theta_2 \tag{3}$$

$$\cos \lambda_1 \sin \theta_1 - \sin \lambda_1 \cos \delta_1 \cos \theta_1 = \sin \delta_2 \cos \theta_2 \tag{4}$$

$$- \sin \lambda_1 \sin \delta_1 = - \cos \delta_2 \tag{5}$$

From these we can derive the expression for the constraint of perpendicularity between the two planes

$$\tan \delta_1 \tan \delta_2 \cos (\theta_1 - \theta_2) = - 1 \tag{6}$$

and the reciprocal relations

$$\cos \delta_1 = \sin \lambda_2 \sin \delta_2 \tag{7}$$

$$\cos \delta_2 = \sin \lambda_1 \sin \delta_1 \tag{8}$$

$$\cos \lambda_1 = \sin \delta_2 \sin (\theta_2 - \theta_1) \tag{9}$$

$$\cos \lambda_2 = \sin \delta_1 \sin (\theta_1 - \theta_2) \tag{10}$$

Hence, having found one solution for θ_1, δ_1, λ_1, we find θ_2, δ_2, λ_2 by finding δ_2 from equation (8) where δ_2 is defined to be between 0° and 180°. In order to find λ_2 we use equations (7), (9), and (10) and then we can fit λ_2 into the correct quadrant. Finally, we compute θ_2 by using equations (6) and (9) and thus we can fit θ_2 into the correct quadrant. When, $90° < \delta_2 \leq 180°$, it signifies that the dip direction lags 90° behind the strike direction, instead of leading by 90°, according to the sign convention used here.

ESTABLISHING THE METHOD

In order to show that the method yields significant results, the following test cases were tried:

1. Banda Sea Earthquake of March 21, 1964 (reported by Teng and Ben Menahem (1965). For this case the calculated amplitudes were also input to check that the method gives back the exact input values.

2. Rat Island Earthquake of 5 February 1965 (origin time 09 32 9.3). The Rat Island earthquake mechanisms were reported by Stauder (1968). The information for the first motion directions for the Rat Island sequence was kindly supplied by the Rev. William Stauder, S.J. in a private communication.

3. Rat Island Earthquake of 1 October 1965

4. Rat Island Earthquake of 15 May 1966.

5. Rat Island Earthquake of 4 July 1966.

6. Rat Island Earthquake of 22 November 1965.

7. Hindu-Kush Earthquake of 28 January 1964. Fault plane solutions were reported by Hedayati and Hirasawa (1966), and also by Ritsema (1966).

8. Alaskan Earthquake of 28 March 1964 (origin time 03 36 14.2). The input data was taken from the Bulletin of the International Seismological Centre. Solutions were reported by Stauder et al (1966) , and Harding et al (1968).

9. Niigata Earthquake of 16 June, 1964. A fault plane solution was reported by Hirasawa (1965).

INPUT DATA

Input data were collected mainly from the C & GS Earthquake Data Reports and the Bulletin of the International Seismological Center, Edinburgh.

The first motion data for the Banda Sea earthquake were taken from Teng and Ben Menahem (1965).

The first motion data for the Rat Island earthquakes were supplied by the Rev. William Stauder, S.J., in a private communication.

The first motion data for the Hindu-Kush earthquake were taken from Hedayati and Hirasawa (1966).

The additional first motion data for the Alaskan earthquake were supplied by Harding in a preprint.

The first motion data for the Niigata earthquake were taken from Hirasawa (1965).

Analysis of the Data

1. Banda Sea Earthquake of the 21st of March 1964. For this earthquake 37 stations were used, 12 of them with magnitude and 25 with only first motions. Figure 1 shows the observed radiation pattern and Table 3 shows the input data. Figure 2 shows the calculated radiation pattern and Table 4 gives the results in tabular form. In our final solution, 36 stations had the same calculated and observed first motion direction and the one disagreement was near a nodal value. The new mean value of m_b came out to be 5.85 as against the C&GS value of 5.8. The stars in Figure 2 are calculated amplitudes for those stations which had observed values and the dots are calculated amplitudes for those stations which only reported first motion directions.

2. Rat Island Earthquake of the 5th of February 1965 (9h.) Figure 3 shows the observed radiation pattern. For this case 72 stations were used, 13 of them with magnitude and 59 with first motions only. The results are given in Figure 4 and Table 5. The resulting score was 72-12, i.e., 12 stations had the opposite calculated first motion. However, this earthquake showed clearly that the C&GS value of m_b was too low since most of the observations were near nodes. The new value of m_b was 6.3 as against the C&GS value of 5.9.

3. Rat Island Earthquake of the 1st of October 1965. This was a case where all the observed first motion consisted of dilatations. Figure 5 shows the observed radiation pattern. The results are given in Figure 6 and Table 6. The score was 80-0. Although the strike angle is quite far from that found by Stauder (1968), the pattern of signs of the first motion are completely similar to Stauder's and the solution was determined primarily by the observed magnitudes.

4. Rat Island Earthquake of the 15th of May 1966. All the observed first motion consisted of compressions. Figure 7 shows the observed radiation pattern. The calculated radiation pattern was also governed mainly by the magnitudes in this case, since the strike angle could be varied considerably without changing any of the signs of the first motion. 84 stations were used, of which 21 reported magnitudes and the rest only first motions. The results are given in Figure 8 and Table 7. This was another case where many of the stations were close to nodes and hence the new value of m_b = 5.96 as against the C&GS value of 5.8 reflects this.

5. Rat Island Earthquake of the 4th of July 1 66. Figure 9 shows the observed radiation pattern. This is a more complicated source mechanism and hence the final score 80-18 shows

that the fit was not too good. 22 stations reported magnitudes and the rest reported first motions only. One of the difficulties was that no magnitudes were reported in the second quadrant, thus missing an entire lobe of the pattern. The results are shown in Figure 10 and Table 8.

6. Rat Island Earthquake of the 22nd of November 1965. This was another case of compressions only, with no stations reporting magnitudes in the second and third quadrant. Figure 11 shows the observed radiation pattern. A change of 30° in the strike angle did not change any of the first motion directions. The results are given in Figure 12 and Table 9.

Another run was made using additional magnitudes supplied by D. Lambert of SDL in a private communication. The new observed radiation pattern is given in Figure 13. For this case, there were magnitudes observed in the third quadrant, but not in the second quadrant. The strike direction did not change, but the dip and slip angles, and hence the second solution, did change somewhat. The results are given in Figure 14 and Table 10.

7. Hindu-Kush Earthquake of the 28th of January 1964. This was a complicated source mechanism. The observed radiation pattern is given in Figure 15. Values of Log_{10} A/T were taken from the ISC bulletin and for the first motion, only those stations used by Hirasawa and Hedayati (1966) were included. The solution favours the one obtained by Ritsema (1966). The final score of 53-14 reflects the inadequacy of the solution. Again, one of the difficulties is that there are no magnitudes observed between 115° and 295° azimuth. The results are shown in Figure 16 and Table 11.

8. Alaskan Earthquake of the 28th of March 1964 (main shock). The 22 values of magnitude for this event were taken from the ISC bulletin and signs of first motion were taken from the bulletin and the C&GS Earthquake Data Reports. The observed radiation pattern is given in Figure 17. The final score obtained, 86-22, suggests that quite a few of the stations reported erroneous first motions, since the solution agress quite well with that of Stauder and Bollinger (1966). The results are given in Figure 18 and Table 12.

Another run was made using additional first motions supplied by Harding in a preprint of the C&GS on the Prince William Sound Earthquakes (1968). The solution was improved considerably and the final score was 134-17. The results are shown in Figure 19 and Table 13.

9. The Niigata Earthquake of the 16th of June 1964. This was another case where m_b given by the C&GS was too low and the new value of 6.5 as against 6.1 is correcting in the right direction. The observed radiation pattern is given in Figure 20. The results, shown in Figure 21 and Table 14, do not agree very well with the solution found by Hirasawa (1965).

CONCLUSIONS

Comparison of the fault plane solutions obtained by the new method and those obtained using first motions only show that indeed it is possible to find reasonable agreement. The solution of the Hindu-Kush earthquake parameters show that although better agreement with the first motion directions was obtained by Hedayati and Hirasawa (1966), the amplitude radiation pattern does not agree as well with the observed pattern as that obtained by using a combination of first motion directions together with observed body-wave magnitudes.

The results of the Rat Island earthquake of the 5th of February, 1965 show that the proposed method compensates correctly where too many of the observed magnitudes were near to nodes. This shows that the proposed definition of magnitude is superior to taking the arithmetic mean of the observations of m_b.

The fault plane solution found by this method is probably not as accurate as that obtained by S-wave data. However, the new method gives two checks on the accuracy obtained, the first by simply the number of differences in sign between calculated and observed, i.e., the "score". The second is by examining the confidence limits of the magnitude.

The results also indicate that in order to take the radiation pattern into account when finding the "true" value of m_b, it is sufficient to use an approximate solution to the source parameters. This is possible by using readily available magnitude and first motion data without laboriously having to re-examine records.

Suggestions for Future Research

1. In order to make best use of the method outlined above,

there still remains to be determined the minimum number of input data which must be used in order to get a good solution. For the cases tried here, rather more points were used than really necessary.

2. Instead of the equal weights least squares solution, it might be possible to get some improvement by using a weighted least squares procedure.

3. If more emphasis is to be placed on the accuracy of the fault plane solution obtained using the new method discussed above, it is possible to add the S-wave data to the least-squares procedure.

4. A still better way to define the "magnitude" of an event may be to use the idea of moment, e.g., Aki (1966).

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TABLE 1

Solution Using The New Method

		PLANE 1			PLANE 2						90% CONFIDENCE	
NO.	DATE	DIP DIR.	DIP	SLIP	DIP DIR.	DIP	SLIP	SCORE	C&GS m_b	MEAN CORRECTED m_b	UPPER LIMIT	LOWER LIMIT
1	Mar 21, 1964	185°	86°	300°	89°	31°	172°	37-1	5.8	5.84	6.0	5.6
2	Feb 5, 1965	145°	82°	100°	17°	12°	38°	72-12	5.9	6.28	6.4	6.0
3	Oct 1, 1965	215°	40°	290°	241°	53°	106°	80-0	6.3	6.36	6.5	6.0
4	May 15, 1966	105°	50°	100°	301°	41°	78°	84-0	5.8	5.96	6.2	5.6
5	Jul 4, 1966	280°	84°	350°	189°	81°	173°	80-18	6.2	6.15	6.4	5.6
6	Nov 22, 1965	180°	60°	80°	341°	31°	106°	66-2	5.9	5.78	5.9	5.6
		180°	50°	70°	331°	43°	112°	88-3		6.07	6.2	6.0
7	Jan 28, 1964	90°	70°	170°	357°	80°	20°	53-14	6.1	6.39	6.5	6.1
8	Mar 28, 1964	135°	80°	30°	231°	61°	168°	86-22	8.5*	7.26	7.6	-
		340°	86°	200°	71°	71°	4°	134-17		7.25	7.4	6.9
9	Jun 16, 1967	135°	60°	140°	23°	56°	37°	71-9	6.1	6.53	6.7	6.1

*The observed values of m_b were too small, the value of 8.5 is not based on them.

TABLE 2

Results Previously Obtained

NO.	DATE	PLANE 1 DIP DIR.	PLANE 1 DIP	PLANE 1 SLIP	PLANE 2 DIP DIR.	PLANE 2 DIP	PLANE 2 SLIP	SCORE	SOURCE
1	Mar 21, 1964	175°	84°	315°					Ben Menahem et al (1965)
2	Feb 5, 1965	141°	75°		325°	15°		63-0	Stauder (1968)
3	Oct 1, 1965	175°	50°		40°	50°		74-0	Stauder (1968)
4	May 15, 1966	136°	61°		349°	34°		67-0	Stauder (1968)
	Alternate	145°	75°		13°	22°		67-0	Stauder (1968)
5	Jul 4, 1966	97°	85°		187°	85°		70-1	Stauder (1968)
6	Nov 22, 1965	145°	70°		354°	22°		56-0	Stauder (1968)
									Hedayati&Hirasawa (1966)
7	Jan 28, 1964	-35.2°±12.8°	21.3°±4.3°	63.0°±12.1°	116.1°±3.8°	71.1°±2.0°	80.0°±4.1°		L.S. Sol. (1)
		-37.5°±12.8°	21.9°±4.2°	65.0°±11.9°	115.8°±3.7°	70.3°±2.1°	80.4°±4.0°		L.S. Sol. (2)
		-118°	25°	54.5°	100°	70	75°		Graph. Sol. (1)
		- 64°	22°	90°	116°	68°	90°		Graph. Sol. (2)
		- 40°	28°	90°	140°	62°	90°		Ritsema (1966)
		- 70°	70°		110°	20°			Aki (1966)
8	Mar 28, 1964	152°	32°		332°	8°			Harding (1968)
		152°	82°		248°	52°			Harding (1968)
		310°	87°		220°	80°			Harding (1968)
		135°	62°		45°	90°			Harding (1968)
9	Jun 16, 1964	101.7°±13.9°	31.2°±1.4°	88.6°±9.8°	-79.9°±5.1°	58.8°±1.3°	89.2°±7.9°		Hirasawa (1965)

Table 3. Example of Input Data for the Banda Sea Earthquake of 21 March 1964.

EQ. BANDA SEA, 21 MARCH,1964, H=367KM, M=5.8

37	1	367.0	80.0	5.0	5	
I	STA(I)	DIST(I)	IW(I)	AZ(I)	MAG(I)	C+/D-
1	ABU	41.76	138.01	9.00	6.40	-
2	COL	93.34	157.50	25.00	5.30	-
3	KIP	77.65	153.05	67.00	5.70	-
4	PMG	19.23	124.19	100.00	5.80	.
5	RIV	34.70	135.38	145.00	6.10	.
6	CAN	34.65	135.36	149.00	5.90	.
7	NHA	20.20	131.27	315.00	5.30	-
8	NUR	102.13	158.00	330.00	5.20	-
9	KJN	100.25	158.00	334.00	5.70	-
10	KEV	99.80	157.98	340.00	5.50	-
11	BAG	23.85	129.35	342.00	5.30	-
12	ANP	32.05	134.32	349.00	6.00	-
13	MAT	43.70	138.64	12.00	-0	.
14	MTJ	43.94	138.67	14.30	-0	.
15	GUA	20.04	131.12	40.30	-0	.
16	HON	77.54	153.02	66.00	-0	.
17	RAB	24.27	129.77	86.00	-0	.
18	WNH	31.88	134.25	97.50	-0	.
19	AFI	59.74	145.86	102.30	-0	.
20	LUG	39.54	137.30	106.60	-0	.
21	PVC	41.09	137.50	109.70	-0	.
22	KOU	37.94	134.68	115.40	-0	.
23	NOU	40.49	137.62	117.10	-0	.
24	CTA	22.45	127.92	129.10	-0	.
25	BHS	31.57	134.11	134.30	-0	.
26	WEL	54.21	143.18	137.30	-0	.
27	TAU	40.24	137.56	157.60	-0	.
28	ADE	30.17	133.55	162.10	-0	.
29	MUN	27.65	132.11	201.60	-0	.
30	PRE	95.93	157.59	243.30	-0	.
31	BUL	96.46	157.55	248.90	-0	.
32	SHI	80.57	154.23	301.40	-0	.
33	IST	100.89	158.00	310.50	-0	.
34	SHL	47.27	140.13	313.70	-0	.
35	HAN	21.90	127.49	342.10	-0	.
36	HKC	31.53	134.11	335.20	-0	.
37	SEO	43.78	138.53	358.90	-0	.

Table 4. Results for the Banda Sea Earthquake of 21 March 1964.

```
XR=  2.4467E 02 CONVR=  1.1562E 02 MEAN MAG= 5.85
95 PERCENT CONF. UPPER LIMIT=  6.0
95 PERCENT CONF. LOWER LIMIT=  5.6
SAMPLE VARIANCE=  3.2126E 03
```

I	STA(I)	AZ(I)	CALC. MAG(I)	C/U	OBS. MAG(I)	C/U
1	ARU	9.0	6.0	-	6.4	-
2	COL	25.0	5.9	-	5.3	-
3	KIP	67.0	5.8	-	5.7	-
4	PMG	100.0	4.9	+	5.8	+
5	RIV	145.0	6.0	+	6.1	+
6	CAN	149.0	6.0	+	5.9	+
7	NHA	315.0	5.5	-	5.3	-
8	NUR	330.0	5.8	-	5.2	-
9	KJN	334.0	5.8	-	5.7	-
10	KEV	340.0	5.8	-	5.5	-
11	BAG	342.0	5.8	-	5.3	-
12	ANP	349.0	5.9	-	6.0	-
13	MAT	12.0	6.1	-	0	-
14	MTJ	14.3	6.1	-	0	-
15	GUA	40.3	6.1	-	0	-
16	HON	66.6	5.8	-	0	-
17	HAB	86.0	5.6	-	0	-
18	HNR	97.5	4.6	-	0	-
19	AFI	102.3	4.5	+	0	-
20	LUG	106.6	5.3	+	0	+
21	PVC	109.7	5.5	+	0	+
22	KOU	115.4	5.6	+	0	+
23	NOU	117.1	5.7	+	0	+
24	CTA	129.1	5.9	+	0	+
25	BRS	134.3	6.0	+	0	+
26	WEL	137.3	5.9	+	0	+
27	TAU	157.8	6.0	+	0	+
28	ADE	162.1	6.1	+	0	+
29	MUN	201.8	5.9	+	0	+
30	PRE	243.3	5.3	+	0	+
31	BUL	248.9	5.2	+	0	+
32	SHI	301.4	5.6	-	0	-
33	IST	310.5	5.6	-	0	-
34	SHL	313.7	5.6	-	0	-
35	MAN	342.1	5.8	-	0	-
36	HKC	335.2	5.8	-	0	-
37	SEO	358.9	6.0	-	0	-

Table 5. Results for the Rat Island Earthquake of 5 February 1964.

```
XBG 7.20000E 01 CONYR= 3.69226E 02 MEAN MAG= 6.28
95 PERCENT CONF. UPPER LIMIT= 6.4
95 PERCENT CONF. LOWER LIMIT= 6.0
SAMPLE VARIANCE= 1.4359E 00
```

I	STATION	AZ(I)	CALC. MAG(I)	C/U	PHS. MAG(I)	C/U
1	KHC	29.1	6.3	+	6.1	+
2	CHC	37.9	6.5	+	6.3	+
3	CPO	59.7	5.1	+	5.4	+
4	WHO	69.0	4.8	+	5.0	+
5	UPO	71.3	5.3	-	5.8	-
6	ALQ	74.2	5.4	-	4.6	+
7	TFO	78.1	5.7	-	5.3	-
8	BUG	269.6	5.1	-	5.6	+
9	DAV	239.9	5.9	+	5.8	+
10	BAG	250.3	6.1	+	6.0	+
11	QUE	301.7	6.4	+	6.2	+
12	NUR	344.0	6.5	+	6.8	+
13	STU	349.9	6.4	+	6.0	+
14	MON	2.2	6.5	+	0	+
15	VAL	7.9	6.5	+	0	+
16	AKU	5.8	6.4	+	0	+
17	ALE	9.4	6.5	+	0	+
18	GDH	19.1	6.4	+	0	+
19	NFS	24.1	6.4	+	0	+
20	COL	42.1	6.3	+	0	+
21	MNT	45.3	6.1	+	0	+
22	BEC	47.2	6.1	+	0	+
23	ORD	48.9	6.0	+	0	+
24	SCP	51.1	6.0	+	0	+
25	AAM	53.7	5.9	+	0	+
26	BLA	55.2	5.9	+	0	+
27	SJP	55.7	5.9	+	0	+
28	MDS	56.5	5.8	+	0	+
29	CSC	57.7	5.8	+	0	+
30	ATL	60.3	5.7	+	0	+
31	FLO	60.5	5.7	+	0	+
32	CAR	60.6	5.6	+	0	-
33	OXF	63.0	5.0	+	0	+
34	WCD	63.8	5.4	+	0	+
35	MOZ	67.1	4.3	+	0	+
36	SPO	67.9	4.6	-	0	+
37	DAL	69.2	4.9	+	0	+
38	GOL	69.3	4.5	-	0	+
39	LUB	72.2	5.1	-	0	+
40	JCT	73.1	5.1	-	0	+
41	TUC	79.9	5.7	-	0	+
42	GSC	81.0	5.9	-	0	+
43	RIV	199.1	5.6	-	0	+
44	NAM	205.9	5.6	-	0	+
45	CTA	207.1	5.5	-	0	+
46	MAN	248.7	6.3	+	0	+
47	ANP	256.5	6.2	+	0	+
48	NHA	257.5	6.2	+	0	+
49	HKC	260.0	6.2	+	0	+
50	SEO	264.9	6.2	+	0	+
51	CHG	270.4	6.3	+	0	+
52	SHL	280.7	6.4	+	0	+
53	MAU	281.1	6.4	+	0	+
54	KOD	281.0	6.3	+	0	+
55	POO	289.5	6.4	+	0	+
56	NDI	293.5	6.4	+	0	+
57	LAH	297.4	6.4	+	0	+
58	SHI	311.9	6.4	+	0	+
59	TEH	315.9	6.4	+	0	+
60	JER	326.1	6.4	+	0	+
61	IST	334.3	6.5	+	0	+
62	ATU	337.1	6.4	+	0	+
63	HEU	341.5	6.5	+	0	+
64	AQU	345.9	6.4	+	0	+
65	TRI	346.3	6.4	+	0	+
66	KEV	346.9	6.5	+	0	+
67	KHC	347.2	6.5	+	0	+
68	COP	349.3	6.5	+	0	+
69	KON	351.8	6.5	+	0	+
70	ESK	358.5	6.4	+	0	+
71	TOL	358.7	6.4	+	0	+
72	MAL	359.0	6.4	+	0	+

Table 6. Results for the Rat Island Earthquake of 1 October 1965.

XF= 6.7169E 02 CONVK= 3.0879E 02 MEAN MAG= 6.30
95 PERCENT CONF. UPPER LIMIT= 6.5
95 PERCENT CONF. LOWER LIMIT= 6.0
SAMPLE VARIANCE= 5.8974E 04

I	STA(I)	AZ(I)	CALC. MAG(I)	C/O	OBS. MAG(I)	C/O
1	NOR	2.9	5.7	-	5.3	-
2	ALE	9.5	5.5	-	5.9	-
3	KTG	7.8	5.9	-	6.5	-
4	GDH	20.0	5.9	-	6.0	-
5	MBC	21.4	5.8	-	6.2	-
6	TRN	59.0	6.4	-	6.1	-
7	CPO	61.5	6.3	-	5.9	-
8	ATL	62.3	6.3	-	6.1	-
9	CAR	64.1	6.4	-	6.4	-
10	WMO	70.5	6.3	-	6.0	-
11	ORO	72.0	6.3	-	6.3	-
12	JCT	74.8	6.4	-	6.4	-
13	ALQ	75.4	6.3	-	5.9	-
14	TFO	79.2	6.3	-	5.3	-
15	BKS	82.8	6.3	-	7.1	-
16	PMG	214.2	6.4	-	5.7	-
17	RAB	255.4	6.3	-	6.2	-
18	RAB	255.4	6.3	-	5.5	-
19	POO	292.7	6.4	-	6.4	-
20	NUR	346.2	6.1	-	6.5	-
21	PRU	349.4	6.2	-	6.0	-
22	MOX	351.4	6.2	-	6.1	-
23	COP	351.7	6.2	-	6.4	-
24	STU	352.0	6.2	-	6.2	-
25	KHL	353.2	6.2	-	4.4	-
26	ESK	.8	6.2	-	0	-
27	HAL	2.1	6.3	-	0	-
28	PTO	5.1	6.3	-	0	-
29	VAL	5.3	6.2	-	0	-
30	AKU	7.4	6.0	-	0	-
31	CHG	35.9	5.6	-	0	-
32	MNT	40.9	6.2	-	0	-
33	WES	47.7	6.2	-	0	-
34	BEC	49.8	6.3	-	0	-
35	OGD	50.7	6.3	-	0	-
36	SCP	52.8	6.3	-	0	-
37	AAM	55.1	6.3	-	0	-
38	MDS	57.7	6.2	-	0	-
39	EDM	58.1	6.1	-	0	-
40	BJP	58.9	6.4	-	0	-
41	FLO	61.9	6.3	-	0	-
42	OXF	64.7	6.3	-	0	-
43	SPO	67.5	6.2	-	0	-
44	GOL	70.1	6.3	-	0	-
45	DAL	70.8	6.3	-	0	-
46	LON	71.0	6.2	-	0	-
47	LUB	73.5	6.3	-	0	-
48	DUG	74.1	6.3	-	0	-
49	COR	74.9	6.3	-	0	-
50	HHP	74.9	6.4	-	0	-
51	OUI	79.9	6.5	-	0	-
52	TUC	80.7	6.4	-	0	-
53	GSC	81.9	6.3	-	0	-
54	RAB	158.0	6.5	-	0	-
55	WEL	182.8	6.5	-	0	-
56	CTA	211.0	6.4	-	0	-
57	ADE	211.5	6.5	-	0	-
58	HOW	222.4	6.4	-	0	-
59	DAV	244.2	6.3	-	0	-
60	MNU	250.8	6.4	-	0	-
61	NHA	261.7	6.3	-	0	-
62	ANP	261.9	6.2	-	0	-
63	HKC	265.4	6.3	-	0	-
64	SEO	271.0	6.2	-	0	-
65	SHL	284.5	6.3	-	0	-
66	KOD	284.7	6.4	-	0	-
67	NDI	296.5	6.3	-	0	-
68	LAH	300.7	6.3	-	0	-
69	QUE	304.9	6.3	-	0	-
70	SHI	314.5	6.3	-	0	-
71	TEH	319.0	6.3	-	0	-
72	TAB	323.0	6.3	-	0	-
73	JER	329.2	6.3	[illegible]	0	-
74	CIN	330.7	6.3	-	0	-
75	IST	337.2	6.3	-	0	-
76	ATH	340.2	6.3	-	0	-
77	KEV	349.7	6.3	-	0	-
78	TRI	349.1	6.2	-	0	-
79	BHC	349.[illegible]	6.2	-	0	-
80	AQU	353.[illegible]	6.1	-	0	-

Table 7. Results for the Rat Island Earthquake of 15 May 1966.

MS= [illegible] [illegible] MAG= 5.9[illegible]
95 PERCENT CONF. [illegible] LIMITS 6.[illegible]
95 PERCENT CONF. [illegible] LIMITS 6.[illegible]
SAMPLE VARIANCE [illegible]

I	STATI[illegible]	[illegible]	OBS. MA(I)	C/D	OBS. MA(I)	C/D
1	NOR	3.6	6.0	•	5.5	•
2	ATG	7.2	6.3	•	5.3	•
3	HNC	21.6	6.6	•	5.4	•
4	NP-	21.9	6.5	•	6.7	•
5	NP-	21.4	6.0	•	5.6	•
6	FUC	31.6	6.6	•	5.8	•
7	COL	37.4	5.7	•	5.2	•
8	KEV	56.2	5.9	•	5.8	•
9	CPO	64.[illegible]	5.7	•	6.0	•
10	LAO	66.[illegible]	5.7	•	5.5	•
11	CPN	67.7	6.1	•	6.0	•
12	SFU	70.7	5.6	•	5.7	•
13	WHN	71.4	5.6	•	5.7	•
14	UHU	75.2	5.7	•	6.2	•
15	TFO	82.5	5.6	•	5.4	•
16	ALQ	78.5	5.7	•	5.1	•
17	RIV	204.2	6.6	•	6.4	•
18	WAH	214.1	5.9	•	5.8	•
19	PM[illegible]	217.1	6.0	•	5.8	•
20	MAG	257.4	5.9	•	5.0	•
21	PRU	291.5	6.1	•	5.4	•
22	ESK	2.9	6.1	•	0	•
23	TOL	4.3	6.1	•	0	•
24	MAL	4.5	6.1	•	0	•
25	IFN	5.5	6.1	•	0	•
26	VAL	7.5	6.1	•	0	•
27	PTO	7.7	6.1	•	0	•
28	GDH	21.5	6.6	•	0	•
29	WES	50.2	6.5	•	0	•
30	WFC	52.3	6.0	•	0	•
31	SCP	55.4	5.9	•	0	•
32	AAM	57.7	5.9	•	0	•
33	FOR	61.4	5.7	•	0	•
34	SJP	61.2	6.0	•	0	•
35	FLO	64.7	5.8	•	0	•
36	ATL	65.4	5.9	•	0	•
37	HCH	67.4	5.7	•	0	•
38	OXF	67.5	5.9	•	0	•
39	MMM	68.2	5.6	•	0	•
40	SHA	70.0	5.9	•	0	•
41	BOZ	70.5	5.6	•	0	•
42	BOL	73.3	5.7	•	0	•
43	LON	75.0	5.5	•	0	•
44	BOG	75.9	6.0	•	0	•
45	DUG	77.4	5.6	•	0	•
46	BMP	77.6	6.0	•	0	•
47	JCT	77.8	5.4	•	0	•
48	FUN	80.3	5.6	•	0	•
49	LPS	81.5	5.9	•	0	•
50	DNV	84.0	5.5	•	0	•
51	TUC	84.1	5.7	•	0	•
52	GSC	85.6	5.6	•	0	•
53	GIE	91.9	6.8	•	0	•
54	KIP	104.5	5.5	•	0	•
55	HNR	204.5	6.0	•	0	•
56	CTA	213.9	6.0	•	0	•
57	GUA	231.4	5.9	•	0	•
58	BND	253.[illegible]	6.0	•	0	•
59	MAN	255.7	5.9	•	0	•
60	ANP	263.6	5.9	•	0	•
61	NFO	266.7	6.0	•	0	•
62	HKC	267.2	5.9	•	0	•
63	SFO	271.8	5.8	•	0	•
64	CHG	276.4	6.0	•	0	•
65	SHL	286.3	6.0	•	0	•
66	HOW	286.5	6.0	•	0	•
67	KOD	287.4	6.1	•	0	•
68	POO	295.1	6.1	•	0	•
69	NDI	298.0	6.2	•	0	•
70	LAH	302.7	6.3	•	0	•
71	QUE	307.0	6.1	•	0	•
72	MSH	315.7	6.1	•	0	•
73	SHI	317.6	6.1	•	0	•
74	TAB	325.9	6.1	•	0	•
75	JER	331.[illegible]	6.1	•	0	•
76	IST	339.5	6.1	•	0	•
77	ATU	342.7	6.1	•	0	•
78	NUR	347.5	6.1	•	0	•
79	KEV	349.[illegible]	6.1	•	0	•
80	TRI	351.[illegible]	6.1	•	0	•
81	COP	353.[illegible]	6.[illegible]	•	0	•
82	STU	354.[illegible]	6.1	•	0	•
83	KHL	355.[illegible]	6.[illegible]	•	0	•
84	L[illegible]	355.[illegible]	6.1	•	0	•

Table 8. Results for the Rat Island Earthquake of 4 July 1966.

XMB 1.51598 [illegible] MAG= 6.15
95 PERCENT CONF. UPPER LIMIT= [illegible]
95 PERCENT CONF. LOWER LIMIT= [illegible]
SAMPLE VARIANCE= [illegible]

I	STAT(I)	AZ(I)	CALC. MAG(I)	C/U	OBS. MAG(I)	C/U
1	ALF	10.0	5.7	+	5.4	+
2	MHC	22.4	6.2	+	6.0	+
3	NP-	22.2	6.2	+	5.8	+
4	CMC	37.9	6.3	+	5.7	+
5	BLA	58.8	5.9	+	6.4	+
6	SJG	60.4	5.4	+	6.2	+
7	TRN	60.7	5.2	+	5.9	+
8	CPO	63.2	5.9	+	5.9	+
9	CAR	65.3	5.8	+	6.8	+
10	LAO	65.5	6.2	+	5.0	+
11	SPA	70.1	6.1	+	6.4	+
12	WMO	72.5	5.8	+	6.5	+
13	UBO	74.9	5.9	+	6.5	+
14	DUG	76.0	5.9	+	6.0	+
15	ALQ	77.9	5.7	+	6.3	+
16	TFO	81.0	5.4	+	5.9	+
17	NAH	212.2	5.9	+	5.6	+
18	PMG	215.9	5.9	+	6.5	+
19	POO	293.8	5.5	+	6.9	+
20	QUE	305.0	4.2	+	5.8	+
21	COP	352.6	5.8	-	6.5	-
22	STU	353.7	4.9	-	5.1	-
23	ESK	1.7	5.1	+	0	-
24	NOR	3.3	5.1	+	0	-
25	MAL	3.5	5.2	+	0	-
26	PTO	6.9	5.3	+	0	-
27	VAL	6.5	5.4	+	0	-
28	KTG	8.0	5.6	+	0	-
29	PDA	20.8	5.6	+	0	-
30	GDH	20.9	6.0	+	0	+
31	COL	39.1	6.5	+	0	+
32	WES	49.2	6.6	+	0	+
33	WEC	51.1	5.8	+	0	+
34	SCP	54.9	6.0	+	0	+
35	HRG	56.6	6.0	+	0	-
36	AAM	56.0	6.8	+	0	+
37	SJP	60.2	5.5	+	0	+
38	SLM	63.0	6.0	+	0	+
39	RDC	65.9	5.9	+	0	+
40	HHI	67.3	6.0	+	0	+
41	SHA	68.5	5.7	+	0	+
42	BOZ	69.7	6.1	+	0	+
43	GOL	72.3	5.9	+	0	+
44	LON	73.9	6.1	+	0	+
45	HDN	74.5	5.2	-	0	+
46	HHF	76.2	5.2	-	0	+
47	JCT	76.8	5.5	+	0	+
48	COR	77.0	5.9	+	0	+
49	LPS	80.3	5.3	-	0	+
50	OUI	83.0	5.5	-	0	+
51	TUC	83.8	[illegible]	+	0	+
52	OHV	83.2	5.5	+	0	+
53	TAL	84.0	5.5	-	0	-
54	GIE	90.0	5.8	-	0	+
55	KIP	142.1	[illegible]	-	0	-
56	AFI	173.3	6.3	-	0	-
57	HNR	202.1	4.5	+	0	+
58	RIV	203.0	5.2	-	0	+
59	CTA	212.3	5.6	+	0	+
60	GUA	229.3	6.3	+	0	+
61	DAV	245.0	6.3	+	0	+
62	HNH	251.0	6.6	+	0	-
63	MAN	254.3	5.3	+	0	+
64	HAG	255.0	6.3	+	0	+
65	ANP	262.0	6.3	+	0	+
66	MFD	265.3	6.8	+	0	+
67	HKC	265.7	6.2	+	0	+
68	SEO	270.2	6.3	+	0	+
69	HO-	285.5	5.5	+	0	+
70	NDI	297.5	5.1	+	0	-
71	LAH	301.3	4.9	+	0	-
72	SHI	316.0	5.0	-	0	-
73	JE-	[illegible]	[illegible]	-	0	-
74	HL-	333.0	5.3	-	0	-
75	IST	338.3	[illegible]	-	0	-
76	ATU	341.9	5.1	-	0	-
77	TRI	351.2	[illegible]	-	0	-
78	RHL	354.3	[illegible]	-	0	+
79	KC-	354.7	4.9	-	0	-
80	GSS	355.3	3.5	-	0	-

Table 9. Results for the Rat Island Earthquake of 22 November 1965.

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SDV 1.9200E 02 CHISQ= 4.0000E 01 MEAN MAG= 5.79
95 PERCENT CONF. UPPER LIMIT 6.0
95 PERCENT CONF. LOWER LIMIT 5.6
SAMPLE VARIANCE= 1.0?20E 03
```

I	STATION	AZ(I)	CALC. MAG(I)	C/O	OBS. MAG(I)	C/O
1	NOR	3.3	5.9	.	5.7	.
2	ATQ	4.7	5.9	.	5.7	.
3	ALE	6.9	5.8	.	5.4	.
4	MAC	21.9	5.8	.	5.9	.
5	TON	61.9	5.8	.	6.0	.
6	CPO	63.2	5.8	.	6.1	.
7	STL	64.9	5.8	.	5.7	.
8	CAR	65.0	5.9	.	6.1	.
9	SPO	69.9	5.7	.	4.2	.
10	WMO	73.0	5.7	.	5.5	.
11	UPP	74.2	5.7	.	6.0	.
12	EUR	79.2	5.7	.	5.6	.
13	TFO	91.4	5.7	.	5.7	.
14	TUC	97.9	5.7	.	5.4	.
15	SHL	205.4	5.9	.	5.9	.
16	POO	204.0	5.9	.	5.9	.
17	NUR	347.1	5.9	.	6.3	.
18	KOE	352.0	5.9	.	6.1	.
19	COP	352.0	5.8	.	5.9	.
20	STU	353.2	5.9	.	5.9	.
21	TOL	3.2	5.9	.	0	.
22	MAL	5.3	5.9	.	0	.
23	IFR	6.4	5.9	.	0	.
24	VAL	8.3	5.9	.	0	.
25	COL	38.3	5.5	.	0	.
26	SCP	54.2	5.8	.	0	.
27	MDG	56.0	5.8	.	0	.
28	GEN	56.0	5.9	.	0	.
29	BLA	58.4	5.8	.	0	.
30	SJP	60.9	5.9	.	0	.
31	RCD	66.3	5.6	.	0	.
32	OXF	66.3	5.8	.	0	.
33	SHA	68.2	5.4	.	0	.
34	BOZ	69.3	5.7	.	0	.
35	BSC	69.3	5.4	.	0	.
36	LUB	75.3	5.6	.	0	.
37	BUG	76.2	5.7	.	0	.
38	TOO	206.9	5.9	.	0	.
39	RAN	217.6	5.2	.	0	.
40	CTA	217.6	5.5	.	0	.
41	PMG	219.?	5.4	.	0	.
42	MAN	254.1	5.7	.	0	.
43	BAG	256.5	5.7	.	0	.
44	GNP	267.1	5.7	.	0	.
45	NHA	267.4	5.8	.	0	.
46	HFO	265.2	5.9	.	0	.
47	HKC	265.7	5.9	.	0	.
48	SEO	270.7	5.8	.	0	.
49	CHG	275.9	5.9	.	0	.
50	NDU	285.4	5.9	.	0	.
51	HOO	305.0	5.9	.	0	.
52	NDI	207.9	5.8	.	0	.
53	LAH	301.4	5.9	.	0	.
54	QUE	305.7	5.9	.	0	.
55	MSH	314.2	5.8	.	0	.
56	SHI	316.4	6.0	.	0	.
57	TAB	324.?	6.0	.	0	.
58	JER	330.7	6.0	.	0	.
59	PRO	338.2	6.0	.	0	.
60	IST	338.5	6.0	.	0	.
61	ATH	341.6	6.0	.	0	.
62	KEV	349.1	5.9	.	0	.
63	TRI	350.1	5.8	.	0	.
64	PRU	350.0	5.8	.	0	.
65	KMC	351.1	5.8	.	0	.
66	KON	354.9	5.8	.	0	.

Table 10. Results for the Rat Island Earthquake of 22 November 1965 (additional magnitudes)

RMS 1.5394E 02 CONV?? 7.9240E 01 MEAN MAG 6.0[illegible]
95 PERCENT CONF. UPPER LIMIT 6.2
95 PERCENT CONF. LOWER LIMIT 6.0
SAMPLE VARIANCE 1.0234E 04

I	STATION	AZIM	CALC. MAG(I)	C/U	OBS. MAG(I)	C/U
1	ESK	1.7	6.1	.	6.0	.
2	TOL	3.[illegible]	6.2	.	6.3	.
3	NOR	3.3	5.9	.	5.0	.
4	MAL	3.3	6.2	.	6.0	.
5	VAL	6.3	6.1	.	6.3	.
6	PTO	6.3	6.1	.	5.6	.
7	KTG	8.7	6.0	.	5.7	.
8	ALE	9.9	5.9	.	5.4	.
9	MHC	21.9	5.7	.	5.6	.
10	NP-NT	22.0	5.7	.	5.6	.
11	COL	30.3	3.9	.	5.4	.
12	MN-NB	44.4	6.0	.	6.2	.
13	OGD	52.0	6.0	.	6.2	.
14	SCP	54.2	6.9	.	6.2	.
15	BN-NY	54.3	5.6	.	5.6	.
16	ULA	58.4	6.8	.	5.0	.
17	SJG	60.6	6.1	.	6.3	.
18	TRN	61.0	6.1	.	6.0	.
19	CPO	63.2	6.0	.	6.4	.
20	ATL	64.0	6.0	.	6.4	.
21	HV-PA	64.9	5.0	.	5.7	.
22	EN-PO	65.2	6.0	.	6.3	.
23	SU-PA	65.3	5.6	.	5.5	.
24	RG-SD	65.3	5.9	.	5.9	.
25	DE-FL	65.3	6.0	.	6.4	.
26	WN-SD	65.4	5.9	.	6.3	.
27	CAR	65.6	6.1	.	6.0	.
28	KC-PO	65.7	5.6	.	6.3	.
29	CR-NA	65.8	5.9	.	6.3	.
30	RCD	66.3	5.6	.	6.5	.
31	GOZ	69.3	5.6	.	6.0	.
32	GSC	69.3	5.0	.	5.6	.
33	SPO	69.8	5.6	.	4.2	.
34	GV-TX	72.6	6.0	.	5.6	.
35	BMO	73.6	5.6	.	5.1	.
36	UBO	74.2	5.6	.	0.1	.
37	LUB	75.3	6.0	.	5.6	.
38	DUG	76.2	5.9	.	5.6	.
39	COR	77.5	5.0	.	5.7	.
40	EUR	78.2	5.6	.	5.6	.
41	RN-TX	79.5	5.6	.	5.7	.
42	TFO	81.4	5.6	.	5.3	.
43	TUC	82.9	5.6	.	5.3	.
44	BKS	65.4	5.6	.	4.0	.
45	RIV	203.4	6.1	.	5.6	.
46	CTA	212.6	6.1	.	5.4	.
47	DAV	244.9	6.1	.	5.6	.
48	LEM	251.7	6.2	.	5.7	.
49	MAN	254.1	6.1	.	5.5	.
50	BAG	256.3	6.2	.	5.4	.
51	HKC	265.7	0.2	.	6.0	.
52	SEO	270.5	6.2	.	5.0	.
53	SHL	265.4	6.2	.	6.4	.
54	KOD	285.0	6.2	.	5.7	.
55	POO	294.0	6.2	.	6.3	.
56	NDI	287.9	6.2	.	6.1	.
57	LAH	301.4	6.2	.	0.6	.
58	QUE	305.7	6.2	.	6.1	.
59	SHI	318.4	6.2	.	6.1	.
60	JER	330.7	6.2	.	5.3	.
61	AUA	347.1	6.1	.	6.4	.
62	KEV	349.1	6.1	.	5.0	.
63	TRI	350.1	6.2	.	5.7	.
64	POZ	352.6	6.2	.	6.1	.
65	COP	352.8	6.1	.	6.4	.
66	STU	353.9	6.2	.	5.6	.
67	KON	354.9	6.1	.	6.3	.
68	IFR	4.4	6.2	.	0	.
69	HNG	54.8	6.0	.	0	.
70	AAM	56.8	6.0	.	0	.
71	SJP	60.6	6.1	.	0	.
72	OXF	66.3	6.0	.	0	.
73	SHA	68.2	6.0	.	0	.
74	TCO	408.9	6.1	.	0	.
75	HAU	217.6	5.9	.	0	.
76	PMG	215.9	6.0	.	0	.
77	ANP	267.1	6.2	.	0	.
78	NHA	267.4	6.2	.	0	.
79	MED	265.2	6.2	.	0	.
80	CHG	275.4	6.2	.	0	.
81	HOW	285.4	6.2	.	0	.
82	MSH	314.6	6.2	.	0	.
83	TAB	320.6	6.2	.	0	.
84	WSD	338.2	6.2	.	0	.
85	IST	338.5	6.2	.	0	.
86	ATH	341.6	6.2	.	0	.
87	PRU	350.6	6.2	.	0	.
88	KHC	351.1	6.2	.	0	.

Table 11. Results for the Hindu Kush Earthquake of 28 January 1964.

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XK= 1.60[illegible]E 03 CONVR= 6.[illegible]E 02 MEAN MAG= 6.39
95 PERCENT CONF. UPPER LIMIT= 6.[illegible]
95 PERCENT CONF. LOWER LIMIT= 6.[illegible]
SAMPLE VARIANCE= 2.1[illegible]E 05
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I	STA(I)	AZ(I)	CALC. MAG(I)	C/O	OBS. MAG(I)	C/O
1	UPP	0.	6.4	+	6.3	+
2	MOZ	1.0	6.4	+	6.1	+
3	NP-	3.0	6.4	+	6.1	+
4	[illegible]	6.0	6.4	+	5.6	+
5	LON	9.0	6.3	+	6.2	+
6	MTJ	6[illegible].0	6.1	-	6.1	+
7	AHO	71.0	6.1	-	6.1	+
8	ANP	90.0	5.9	-	5.5	-
9	BAG	103.0	5.4	-	5.9	-
10	PMG	106.0	4.5	-	6.1	-
11	NHA	135.0	5.6	+	5.4	-
12	CHI	295.0	6.6	+	7.0	-
13	LIS	299.0	6.6	+	7.2	+
14	LJU	301.0	6.7	+	6.4	+
15	PSZ	303.0	6.7	+	7.0	+
16	VIE	304.0	6.7	+	6.7	+
17	STU	306.0	6.7	+	5.9	+
18	PRU	307.0	6.7	+	6.5	+
19	MOX	308.0	6.7	+	7.0	+
20	BNS	309.0	6.7	+	6.3	+
21	WAR	310.0	6.8	+	7.2	+
22	KEW	311.0	6.7	+	6.5	+
23	COP	315.0	6.8	+	6.9	+
24	NUR	324.0	6.8	+	7.0	+
25	KTG	336.0	6.7	+	6.4	+
26	BLA	337.0	6.5	+	5.5	+
27	KEV	338.0	6.7	+	6.6	+
28	NOR	358.0	6.6	+	6.2	+
29	RCD	356.0	6.4	+	6.7	+
30	HNR	98.1	4.1	-	0	-
31	RAB	98.5	4.9	-	0	-
32	HKC	98.5	5.5	-	0	-
33	SHL	135.4	6.1	+	0	-
34	CHG	138.0	5.9	+	0	-
35	HUN	142.2	5.3	-	0	+
36	NDI	143.9	6.0	+	0	-
37	QUE	208.0	6.[illegible]	+	0	-
38	PRE	219.5	6.3	-	0	+
39	BUL	222.6	6.3	-	0	+
40	NAI	227.8	6.5	-	0	+
41	WIN	229.8	6.1	-	0	+
42	AAE	234.7	6.5	-	0	+
43	SHI	250.9	6.0	+	0	+
44	HLW	270.3	6.1	+	0	+
45	ATU	288.9	6.6	+	0	+
46	IST	291.0	6.6	+	0	+
47	HAL	294.8	6.6	+	0	+
48	AQU	296.0	6.7	+	0	+
49	TOL	298.1	6.6	+	0	+
50	PTO	301.0	6.6	+	0	+
51	PDA	304.7	6.6	+	0	+
52	VIN	313.3	6.7	+	0	+
53	KOD	321.0	6.8	+	0	+

Table 12. **Results for the Alaskan Earthquake of 28 March 1964.**

Table 13. Results for the Alaskan Earthquake of 28 March 1964 (additional first motions).

[illegible]

Table 14. Results for the Niigata Earthquake of 16 June 1964.

[illegible]
[illegible]
[illegible]
[illegible]

1	[illegible]	[illegible]	[illegible]	.	[illegible]	.
2	[illegible]	[illegible]	[illegible]	.	[illegible]	.
3	[illegible]	[illegible]	[illegible]	.	[illegible]	.
4	[illegible]	[illegible]	[illegible]	.	[illegible]	.
5	[illegible]	[illegible]	[illegible]	.	[illegible]	.
6	[illegible]	[illegible]	[illegible]	.	[illegible]	.
7	[illegible]	[illegible]	[illegible]	.	[illegible]	.
8	[illegible]	[illegible]	[illegible]	.	[illegible]	.
9	[illegible]	[illegible]	[illegible]	.	[illegible]	.
10	[illegible]	[illegible]	[illegible]	.	[illegible]	.
11	[illegible]	[illegible]	[illegible]	.	[illegible]	.
12	[illegible]	[illegible]	[illegible]	.	[illegible]	.
13	[illegible]	[illegible]	[illegible]	.	[illegible]	.
14	[illegible]	[illegible]	[illegible]	.	[illegible]	.
15	[illegible]	[illegible]	[illegible]	-	[illegible]	.
16	[illegible]	[illegible]	[illegible]	.	[illegible]	.
17	[illegible]	[illegible]	[illegible]	.	[illegible]	.
18	[illegible]	[illegible]	[illegible]	.	[illegible]	.
19	[illegible]	[illegible]	[illegible]	.	[illegible]	.
20	[illegible]	[illegible]	[illegible]	.	[illegible]	.
21	[illegible]	[illegible]	[illegible]	.	[illegible]	.
22	[illegible]	[illegible]	[illegible]	.	[illegible]	.
23	[illegible]	[illegible]	[illegible]	.	[illegible]	.
24	[illegible]	[illegible]	[illegible]	.	[illegible]	.
25	[illegible]	[illegible]	[illegible]	.	[illegible]	.
26	[illegible]	[illegible]	[illegible]	.	[illegible]	.
27	[illegible]	[illegible]	[illegible]	.	[illegible]	.
28	[illegible]	[illegible]	[illegible]	.	[illegible]	.
29	[illegible]	[illegible]	[illegible]	.	[illegible]	.
30	[illegible]	[illegible]	[illegible]	.	[illegible]	.
31	[illegible]	[illegible]	[illegible]	.	[illegible]	.
32	[illegible]	[illegible]	[illegible]	.	[illegible]	.
33	[illegible]	[illegible]	[illegible]	.	[illegible]	.
34	[illegible]	[illegible]	[illegible]	.	[illegible]	.
35	[illegible]	[illegible]	[illegible]	.	[illegible]	.
36	[illegible]	[illegible]	[illegible]	.	[illegible]	.
37	[illegible]	[illegible]	[illegible]	.	[illegible]	.
38	[illegible]	[illegible]	[illegible]	.	[illegible]	.
39	[illegible]	[illegible]	[illegible]	.	[illegible]	.
40	[illegible]	[illegible]	[illegible]	.	[illegible]	.
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43	[illegible]	[illegible]	[illegible]	.	[illegible]	.
44	[illegible]	[illegible]	[illegible]	.	[illegible]	.
45	[illegible]	[illegible]	[illegible]	.	[illegible]	.
46	[illegible]	[illegible]	[illegible]	.	[illegible]	.
47	[illegible]	[illegible]	[illegible]	.	[illegible]	.
48	[illegible]	[illegible]	[illegible]	.	[illegible]	.
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54	[illegible]	[illegible]	[illegible]	.	[illegible]	.
55	[illegible]	[illegible]	[illegible]	.	[illegible]	.
56	[illegible]	[illegible]	[illegible]	.	[illegible]	.
57	[illegible]	[illegible]	[illegible]	.	[illegible]	.
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60	[illegible]	[illegible]	[illegible]	.	[illegible]	.
61	[illegible]	[illegible]	[illegible]	.	[illegible]	.
62	[illegible]	[illegible]	[illegible]	.	[illegible]	.
63	[illegible]	[illegible]	[illegible]	.	[illegible]	.
64	[illegible]	[illegible]	[illegible]	.	[illegible]	.
65	[illegible]	[illegible]	[illegible]	.	[illegible]	.
66	[illegible]	[illegible]	[illegible]	.	[illegible]	.
67	[illegible]	[illegible]	[illegible]	.	[illegible]	.
68	[illegible]	[illegible]	[illegible]	.	[illegible]	.
69	[illegible]	[illegible]	[illegible]	.	[illegible]	.
70	[illegible]	[illegible]	[illegible]	.	[illegible]	.
71	[illegible]	[illegible]	[illegible]	.	[illegible]	.

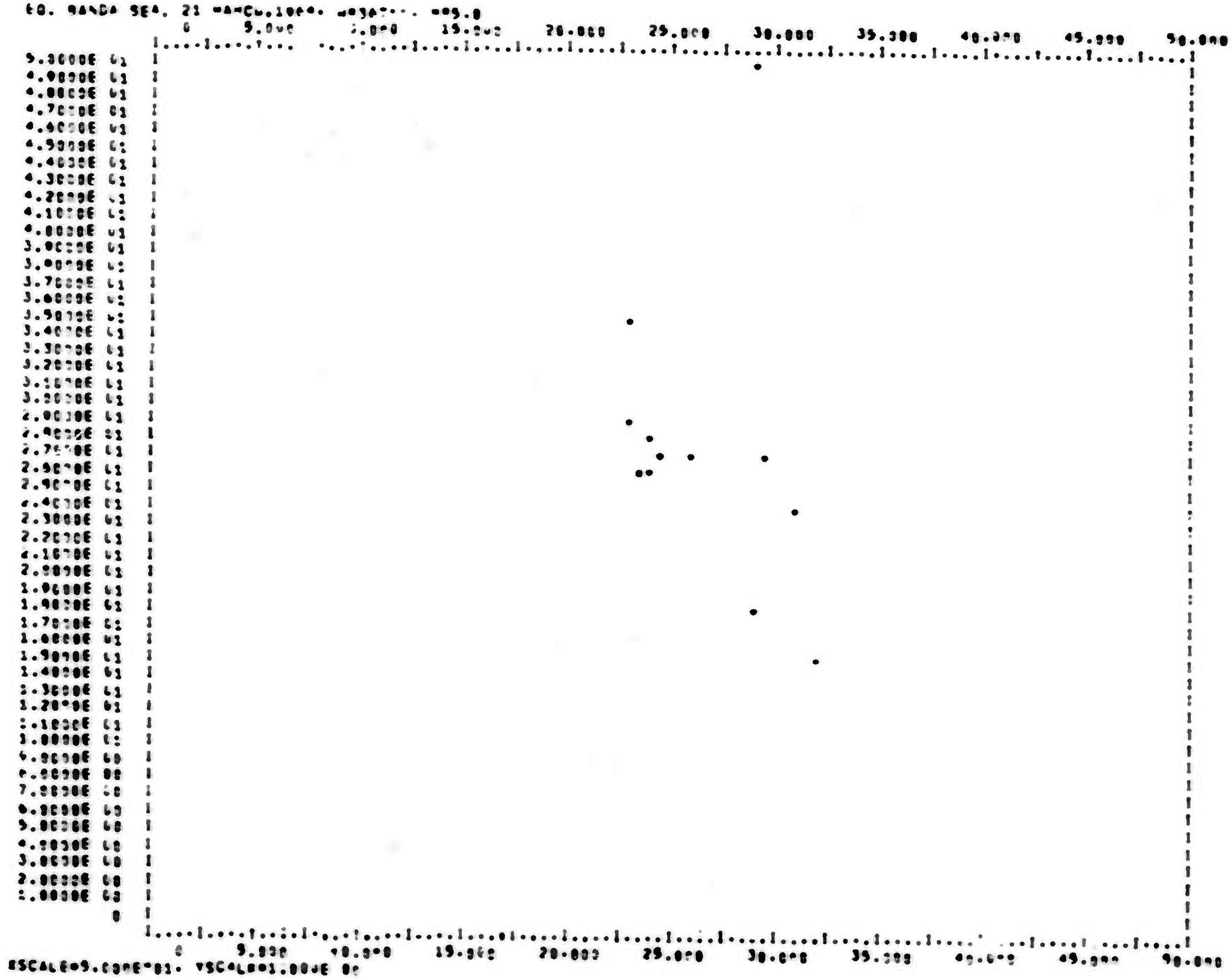


Figure 1. Observed Radiation Pattern for the Banda Sea Earthquake of 21 March 1964.

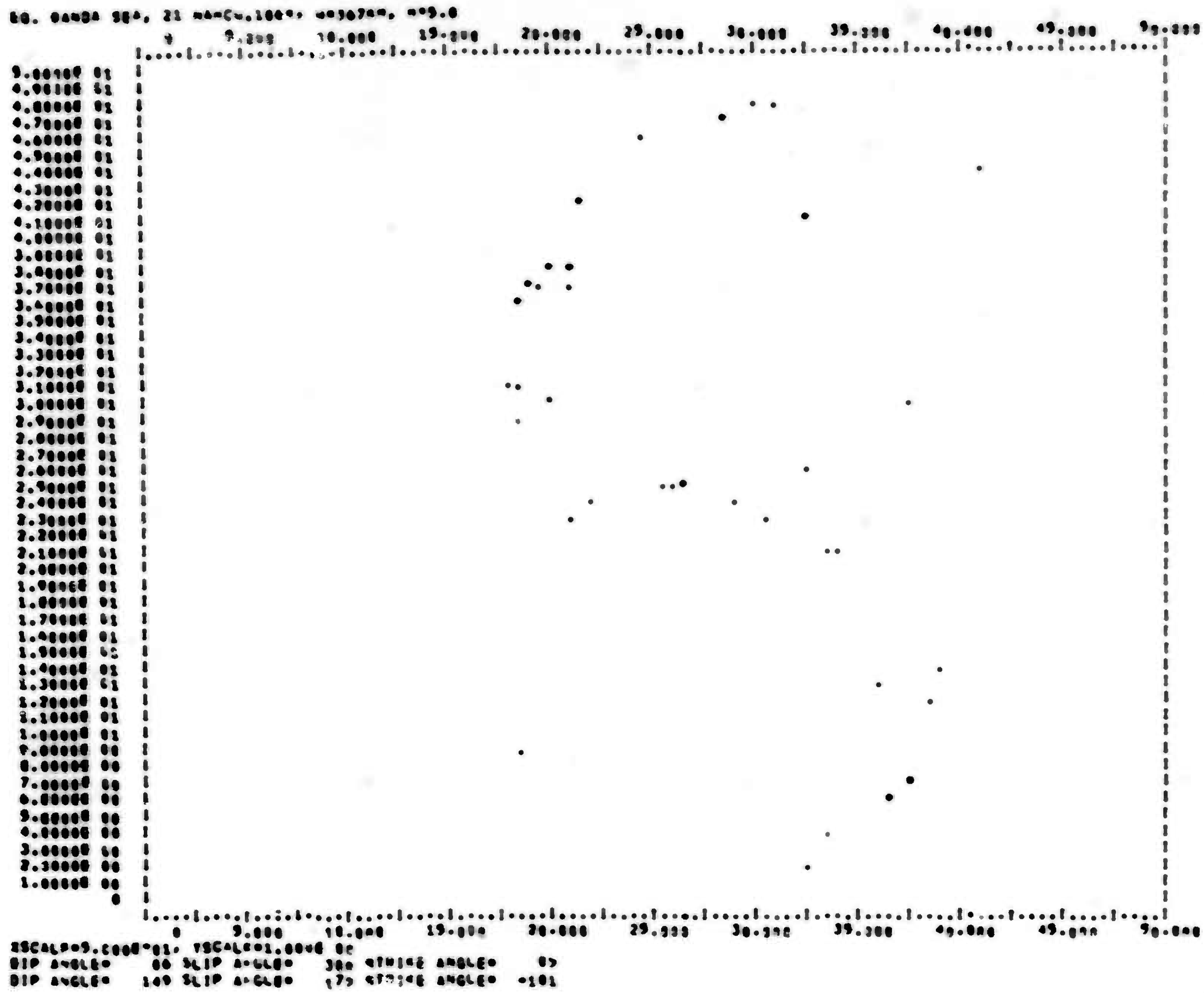


Figure 2. Calculated Radiation Pattern for the Banda Sea Earthquake of 21 March 1964.

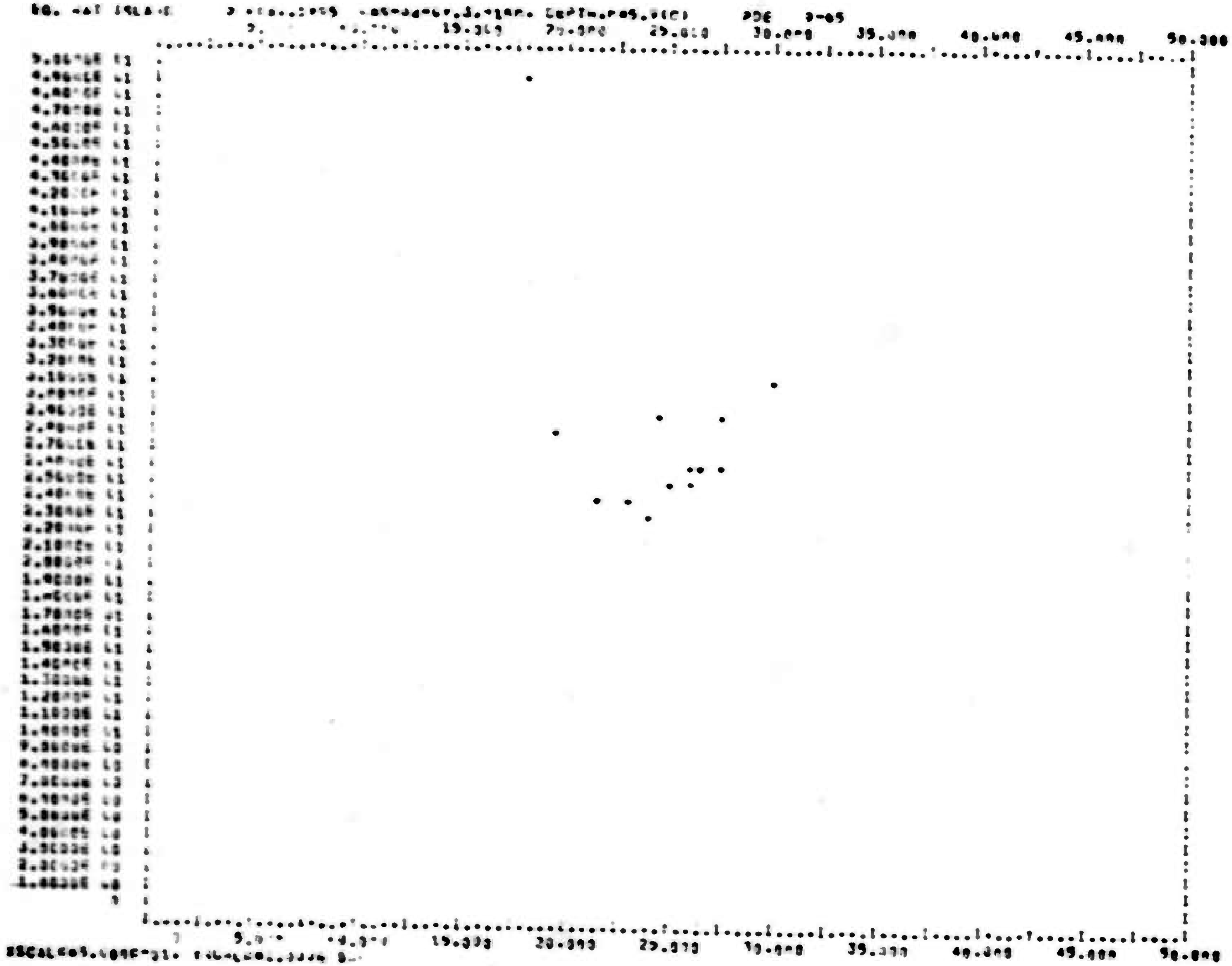


Figure 3. Observed Radiation Pattern for the Rat Island Earthquake of 5 February 1965.

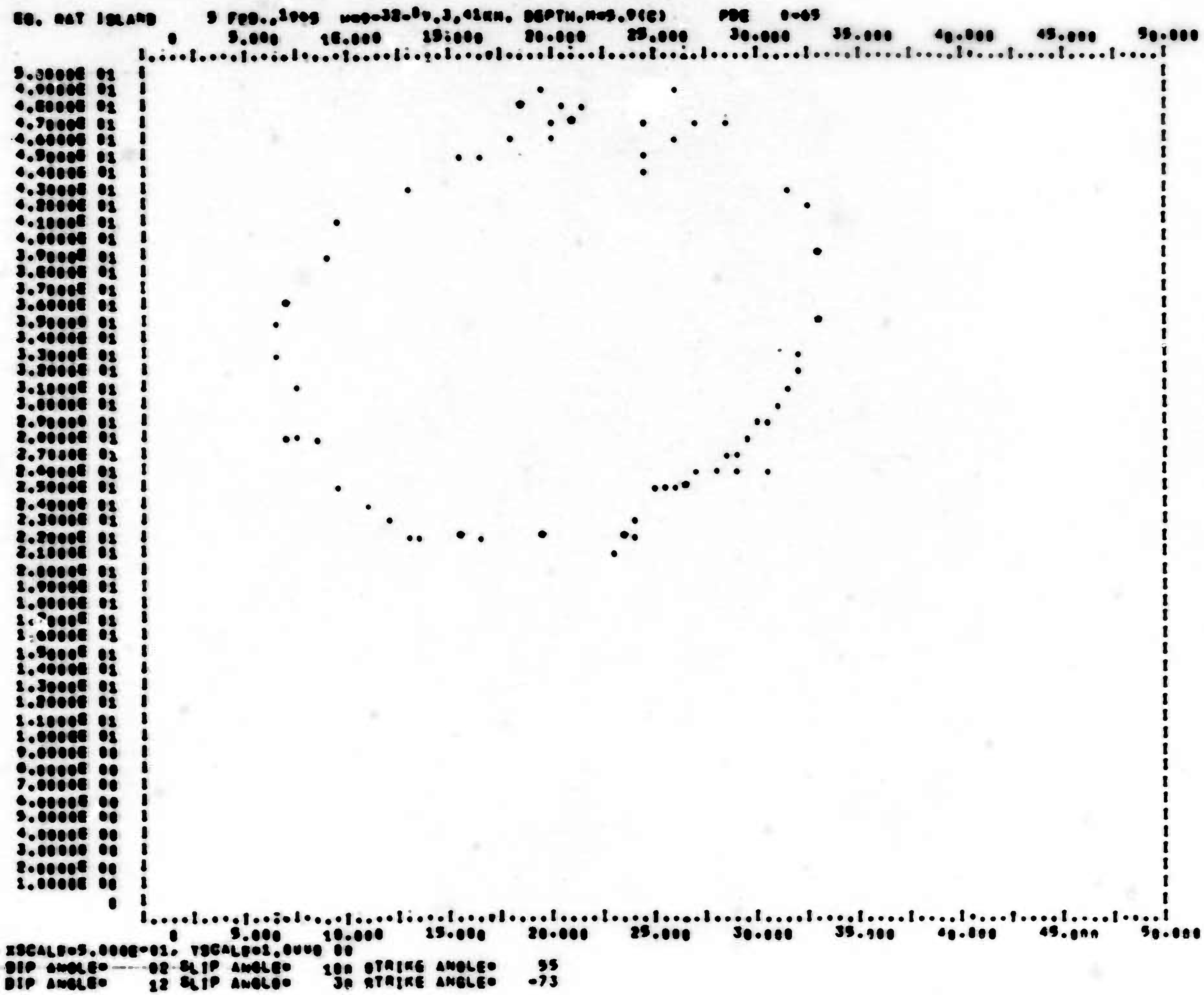


Figure 4. Calculated Radiation Pattern for the Rat Island Earthquake of 5 February 1965.

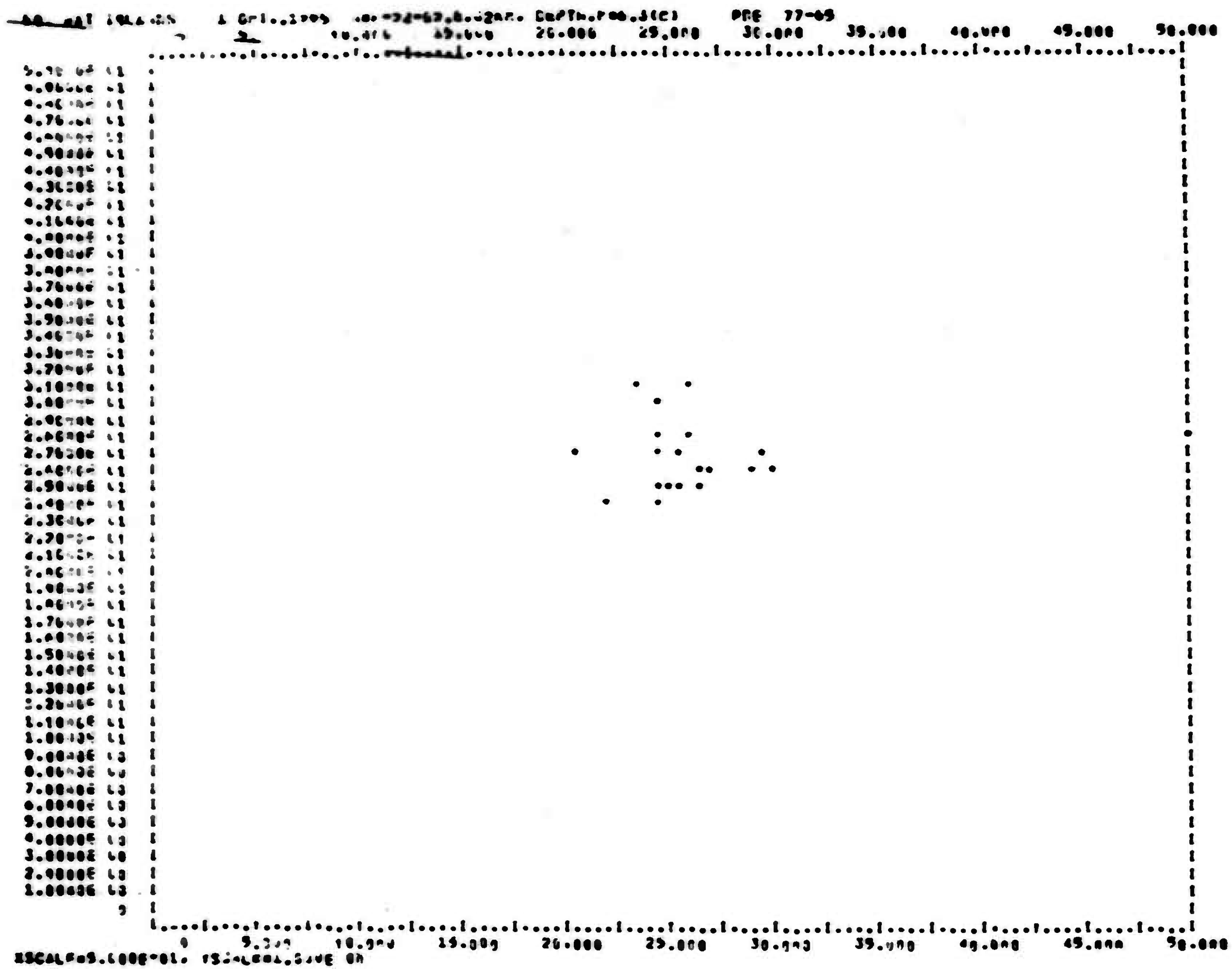


Figure 5. Observed Radiation Pattern for the Rat Island Earthquakd of 1 October 1965.

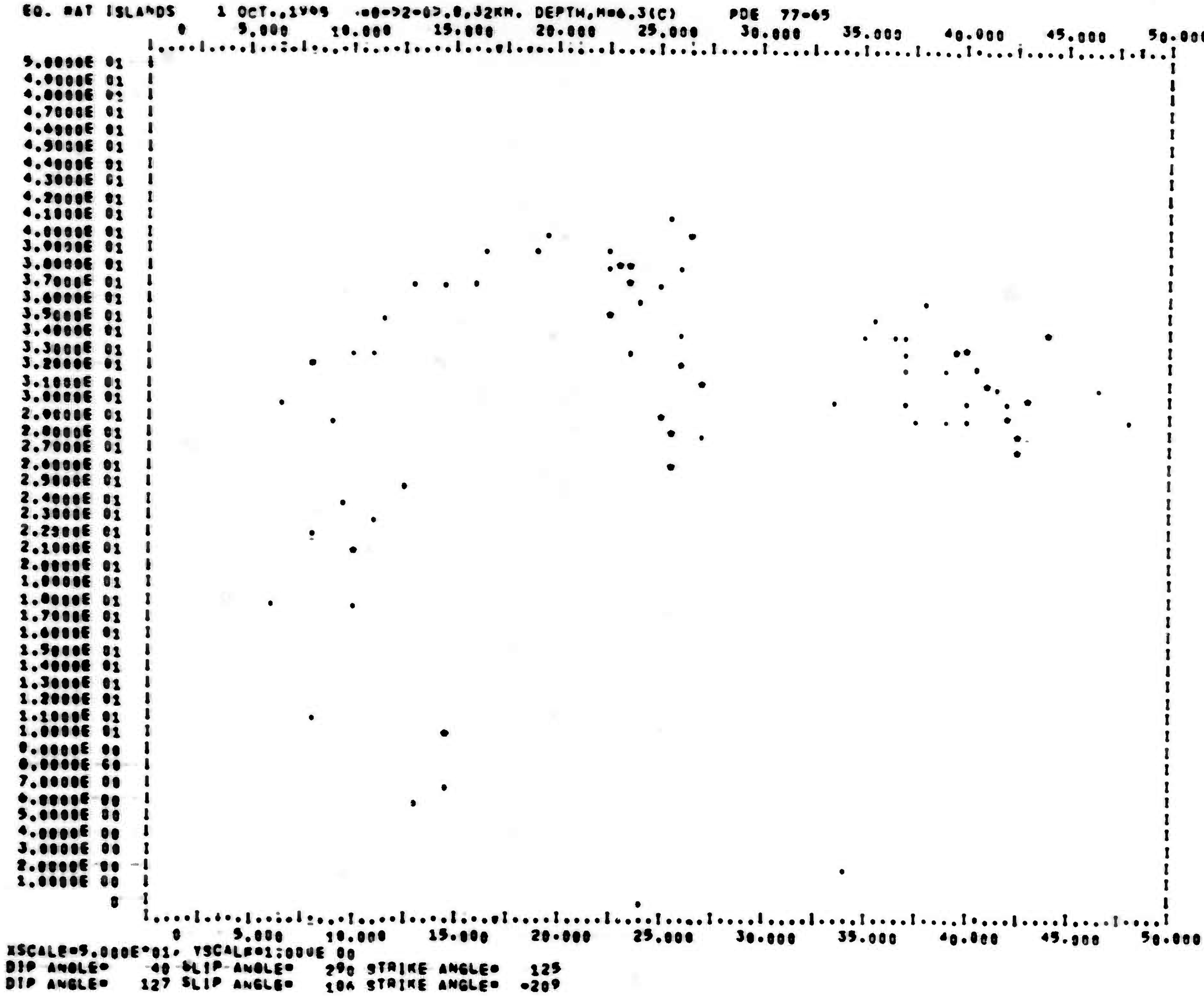


Figure 6. Calculated Radiation Pattern for the Rat Island Earthquake of 1 October 1965.

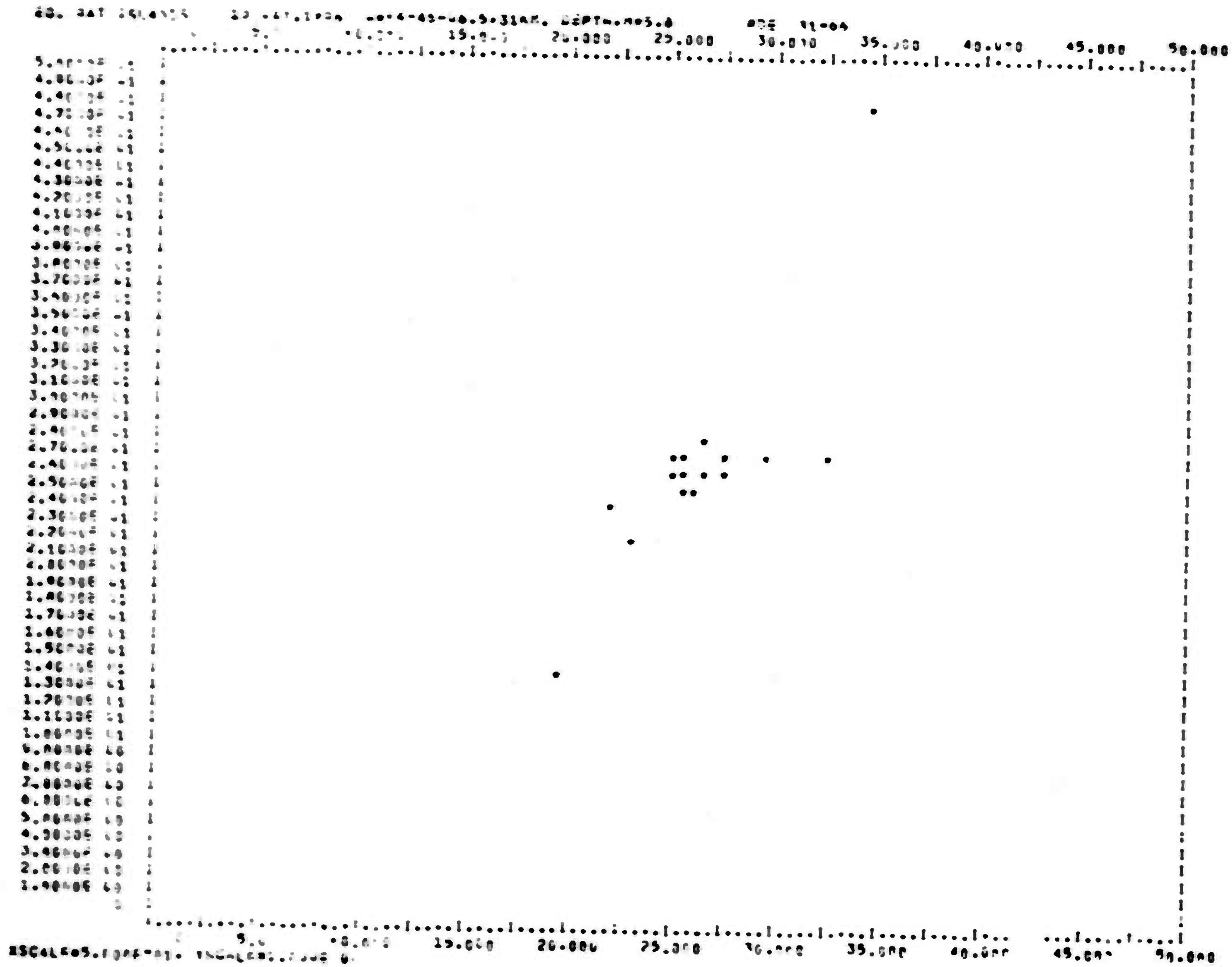


Figure 7. Observed Radiation Pattern for the Rat Island Earthquake of 15 May 1966.

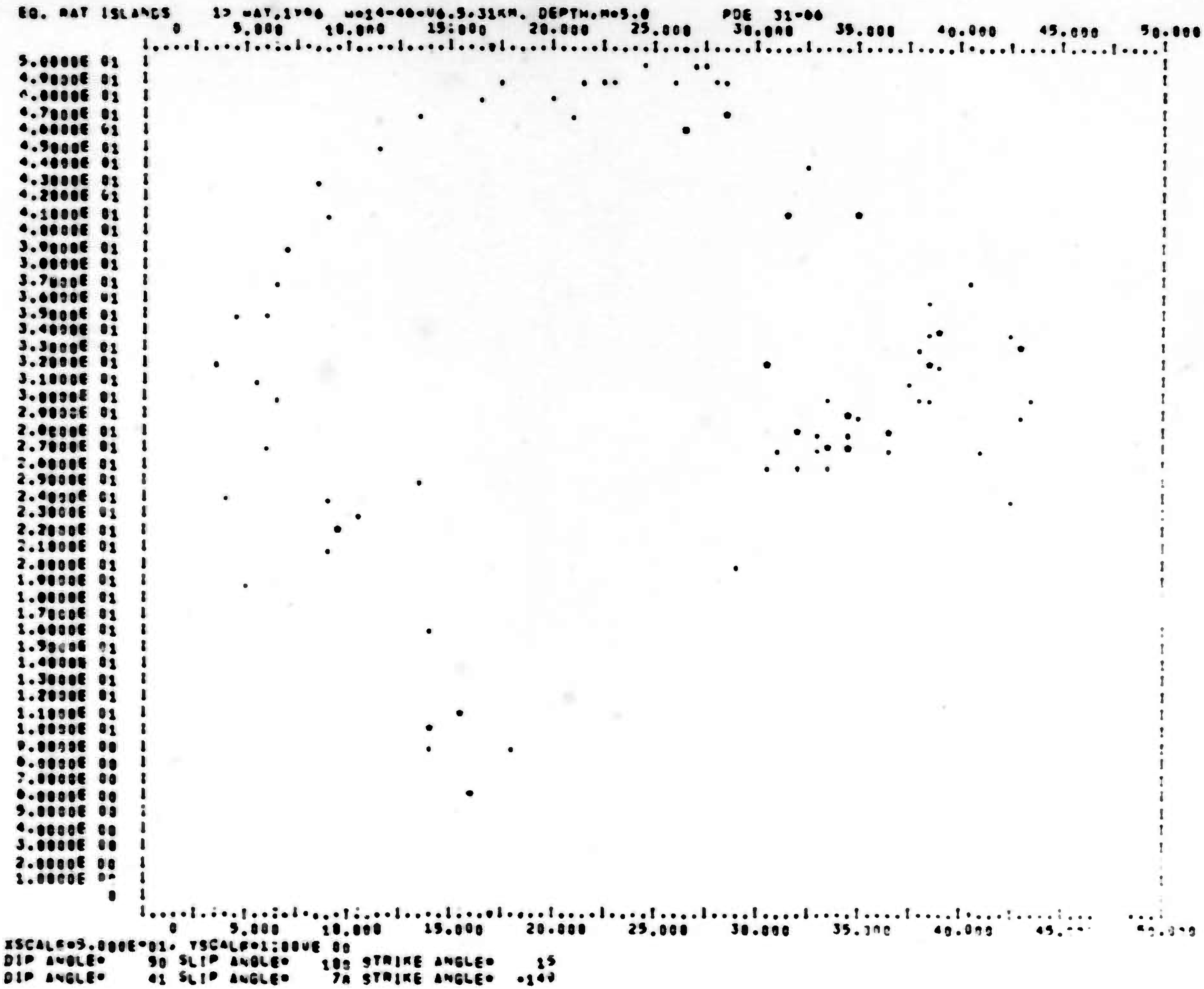


Figure 8. Calculated Radiation Pattern for the Rat Island Earthquake of 15 May 1966.

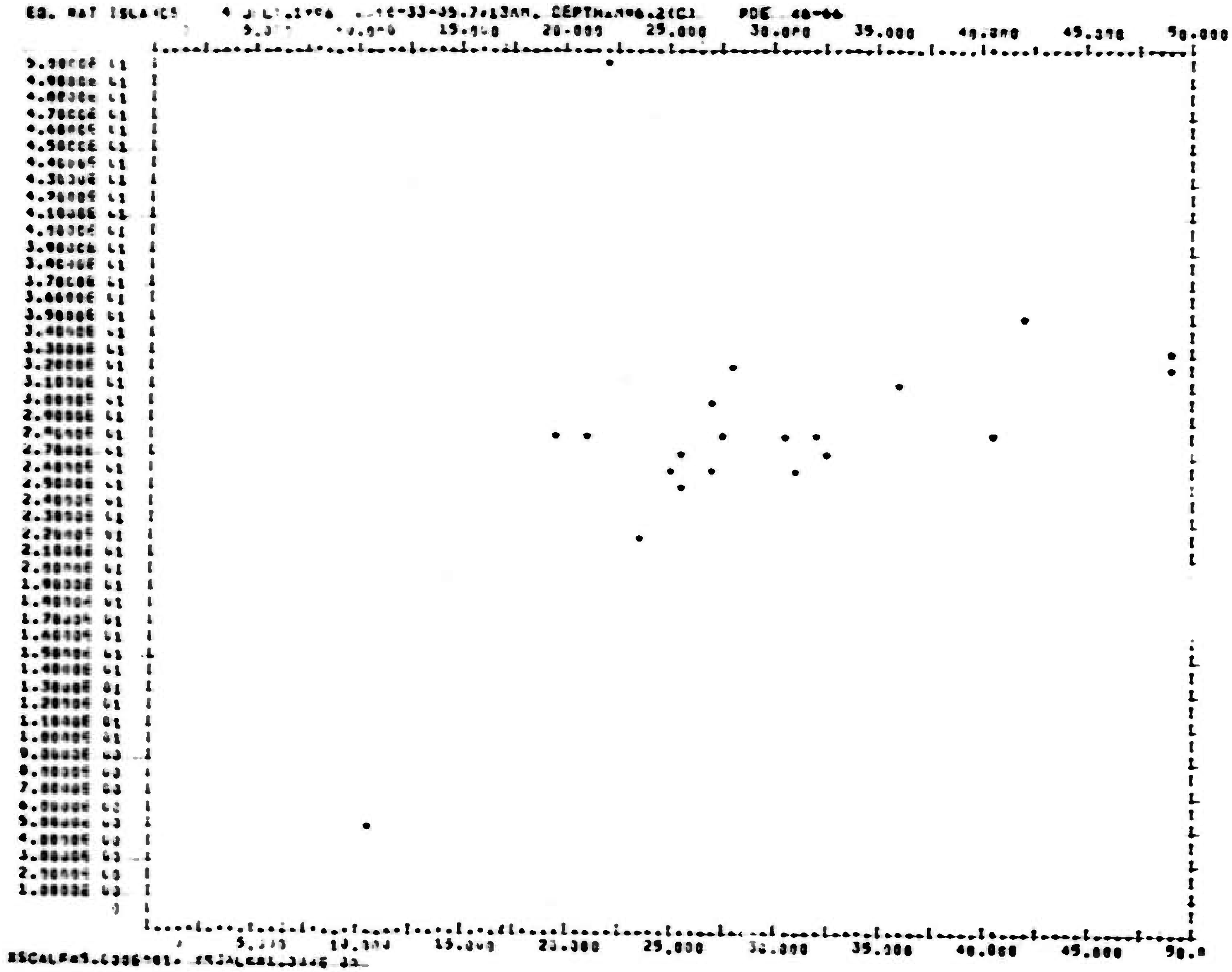


Figure 9. Observed Radiation Pattern for the Rat Island Earthquake of 4 July 1966.

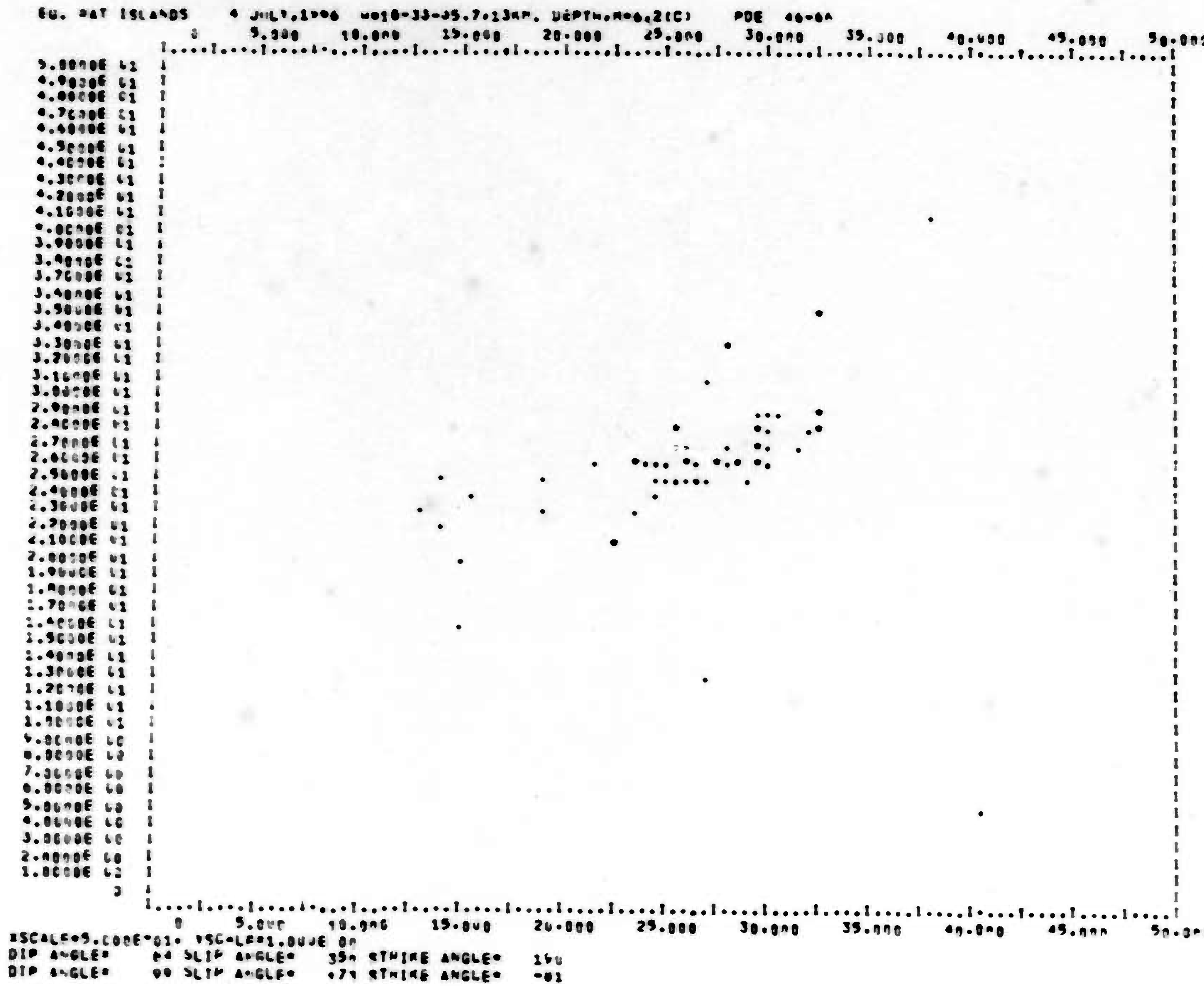


Figure 10. Calculated Radiation Pattern for the Rat Island Earthquake of 4 July 1966.

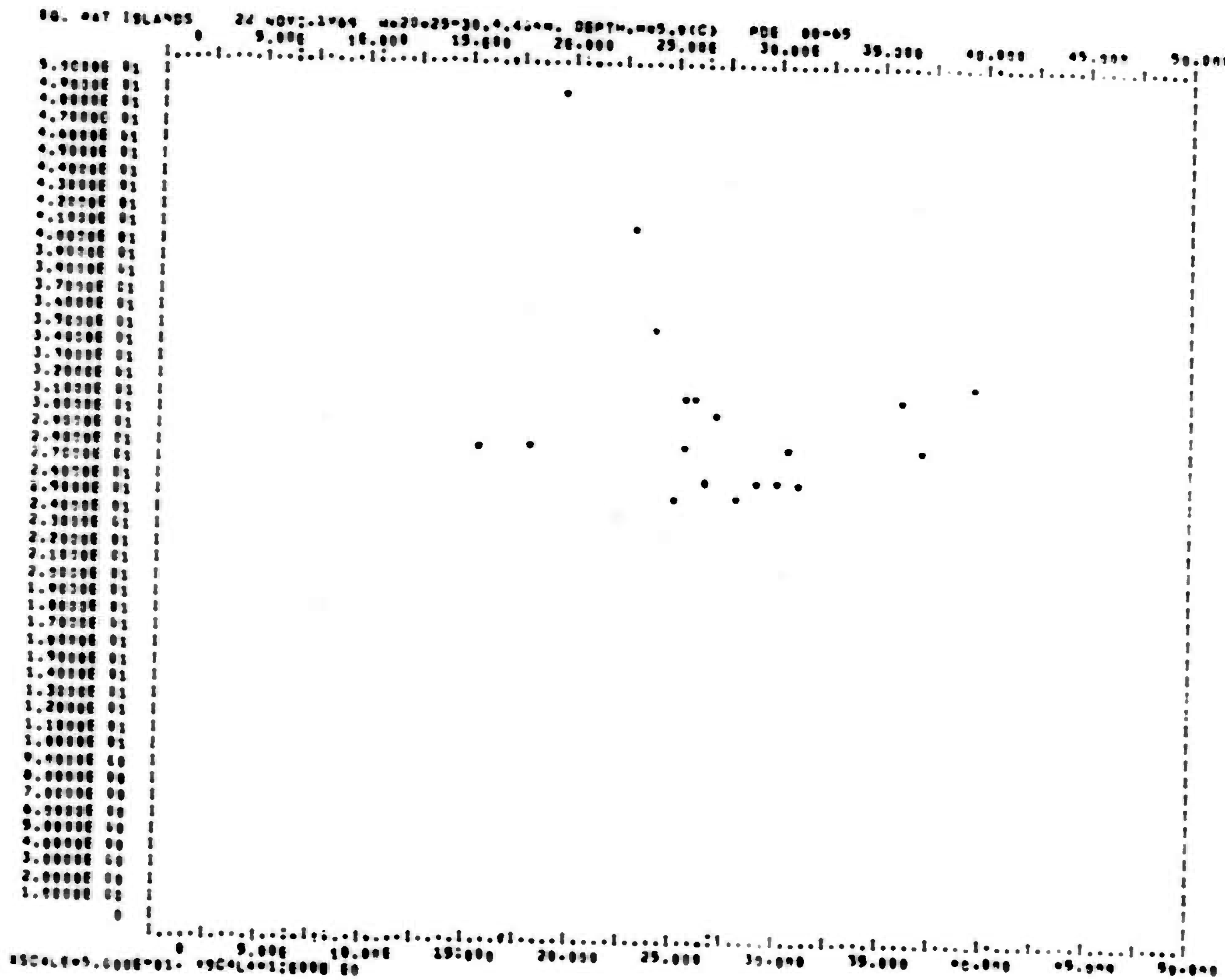


Figure 11. Observed Radiation Pattern for the Rat Island Earthquake of 22 November 1965.

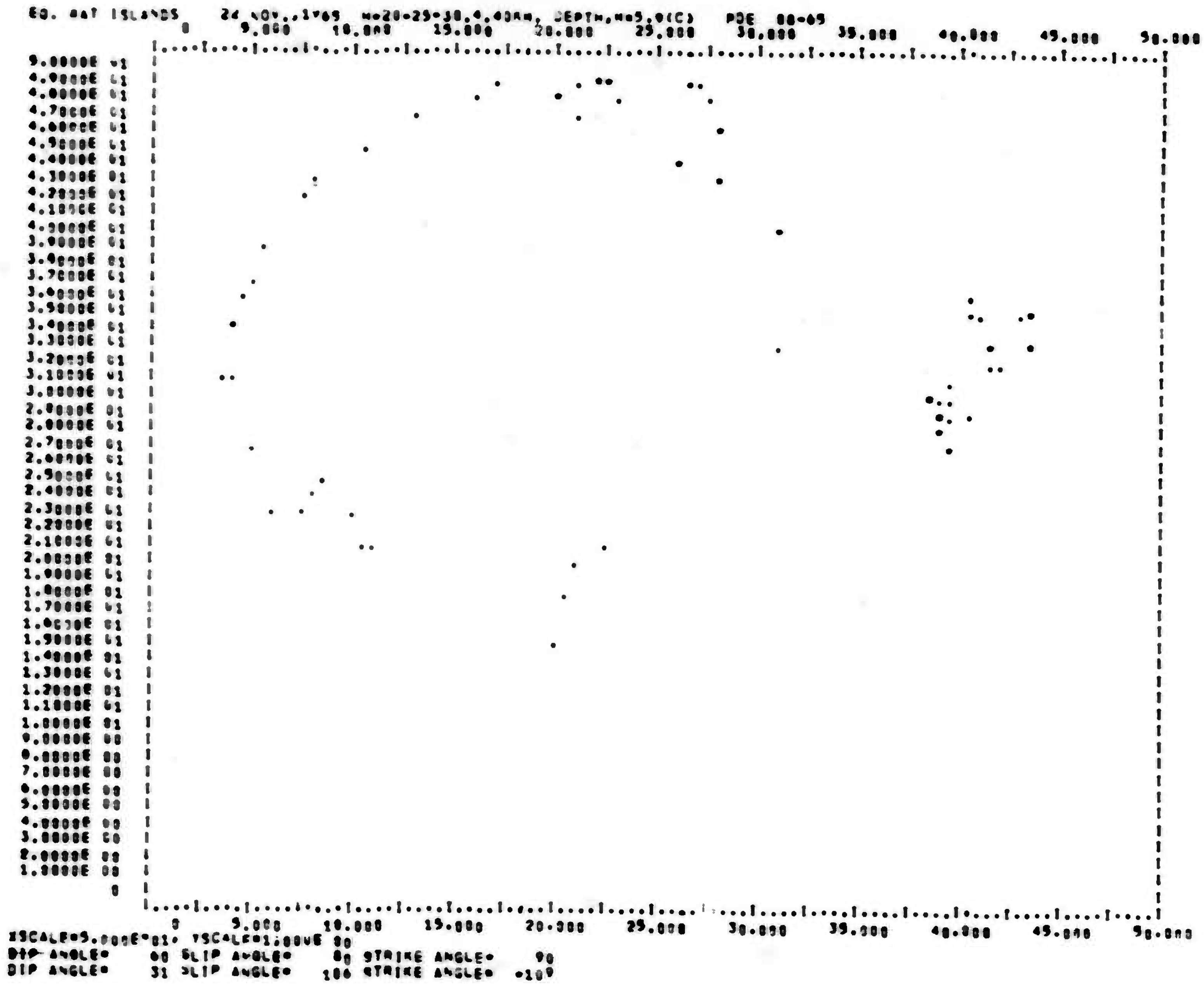


Figure 12. Calculated Radiation Pattern for the Rat Island Earthquake of 22 November 1965.

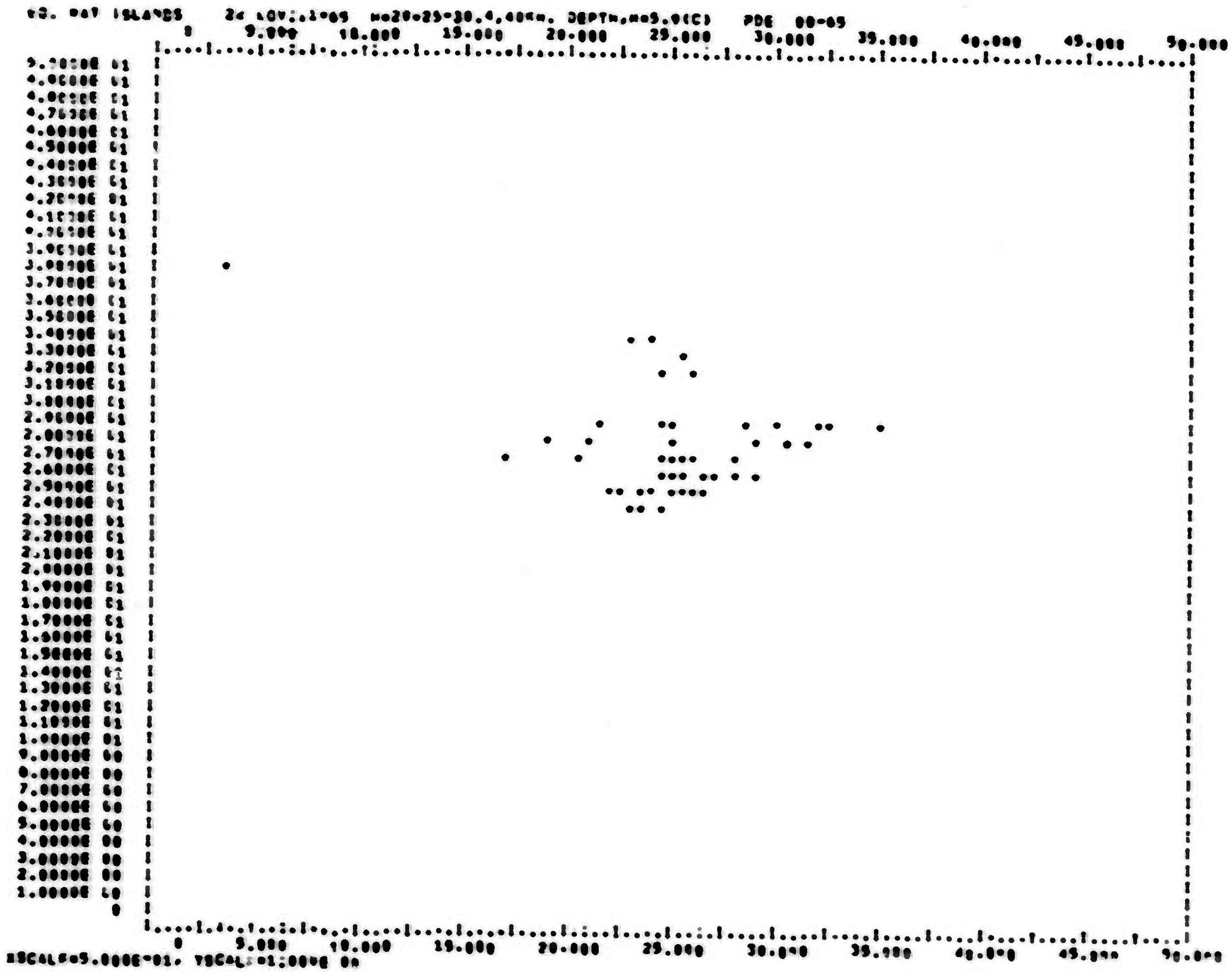


Figure 13. Observed Radiation Pattern for the Rat Island Earthquake of 22 November 1965 (additional magnitudes).

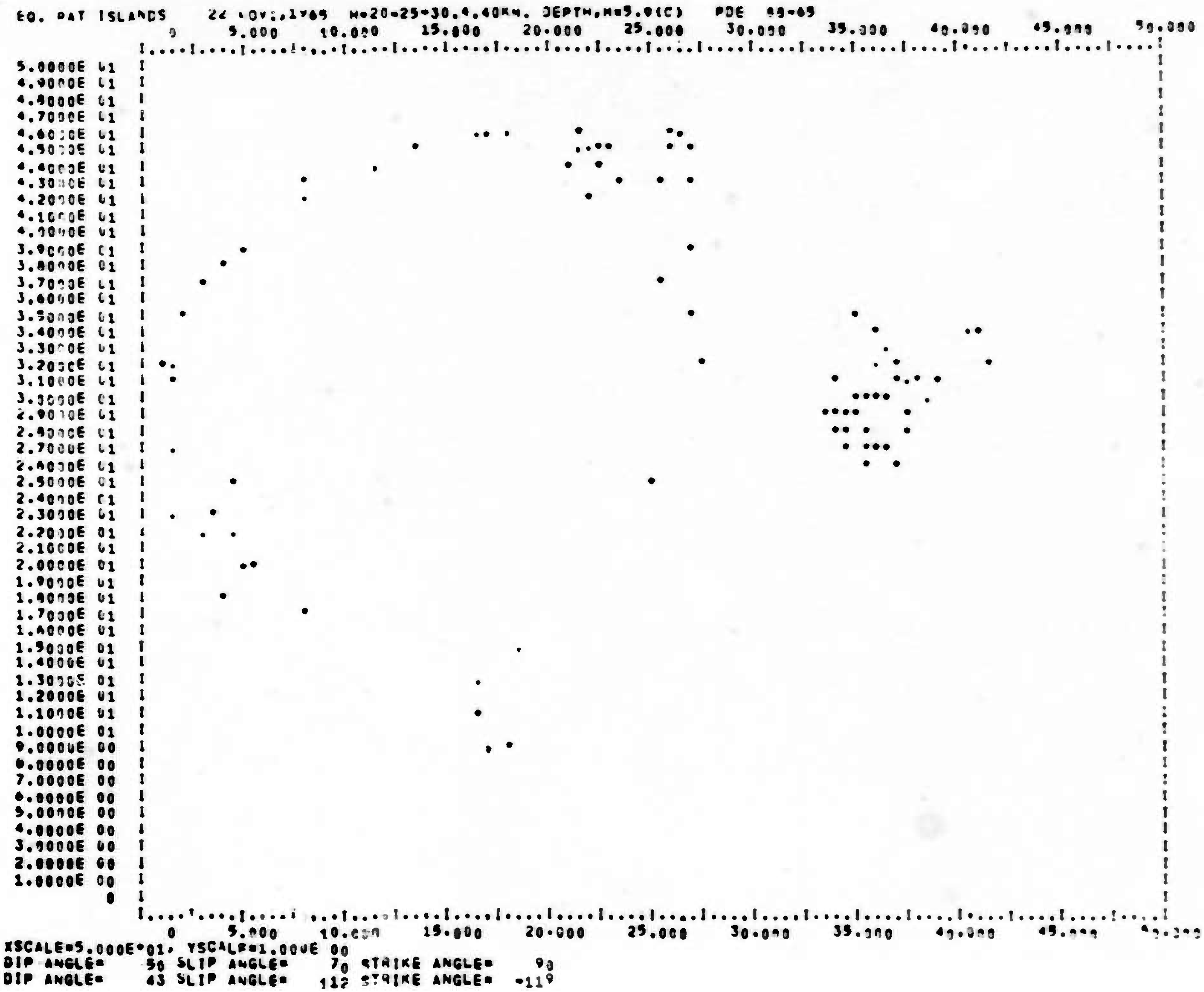


Figure 14. Calculated Radiation Pattern for the Rat Island Earthquake of 22 November 1965 (additional magnitudes).

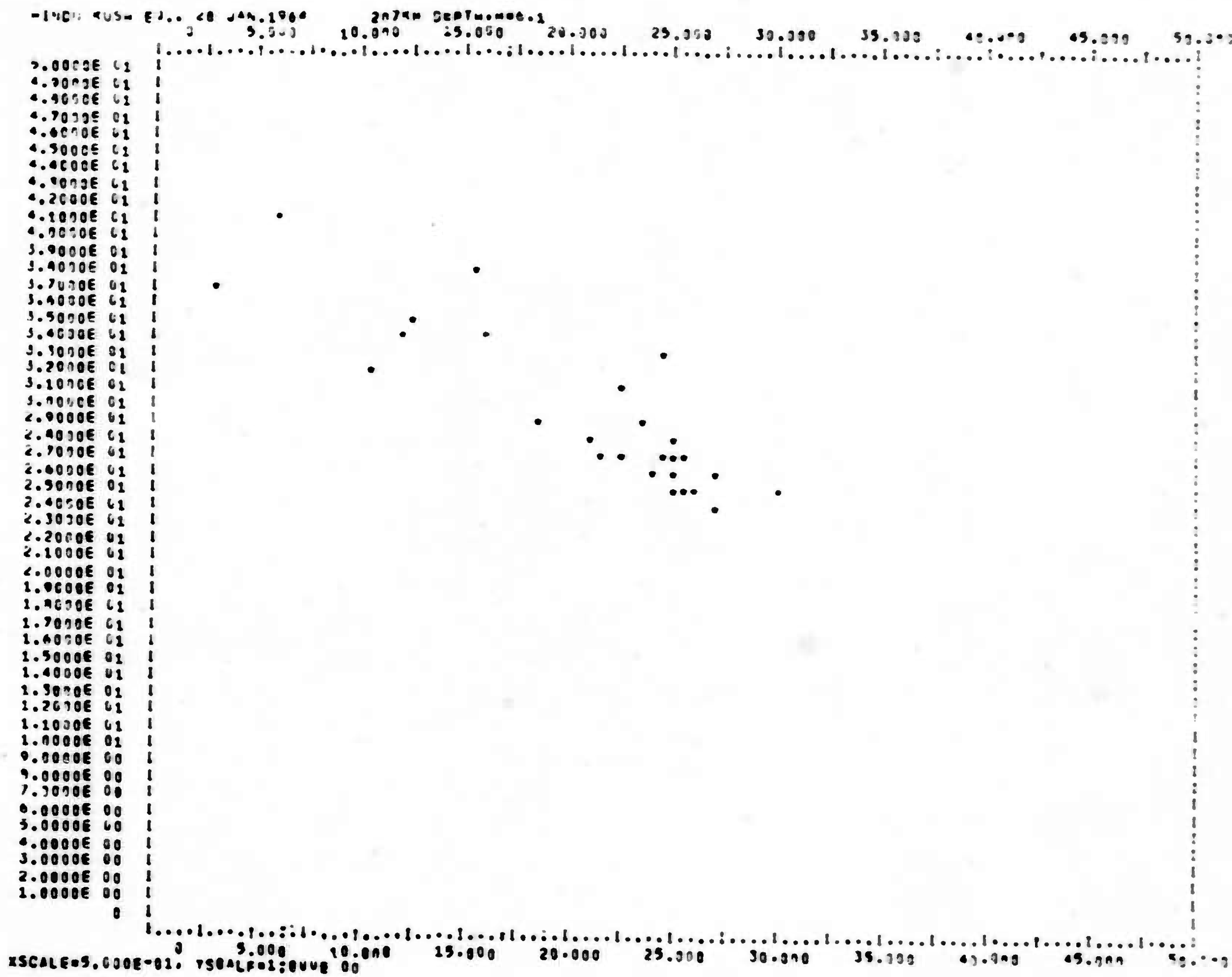


Figure 15. Observed Radiation Pattern for the Hindu Kush Earthquake of 28 January 1964.

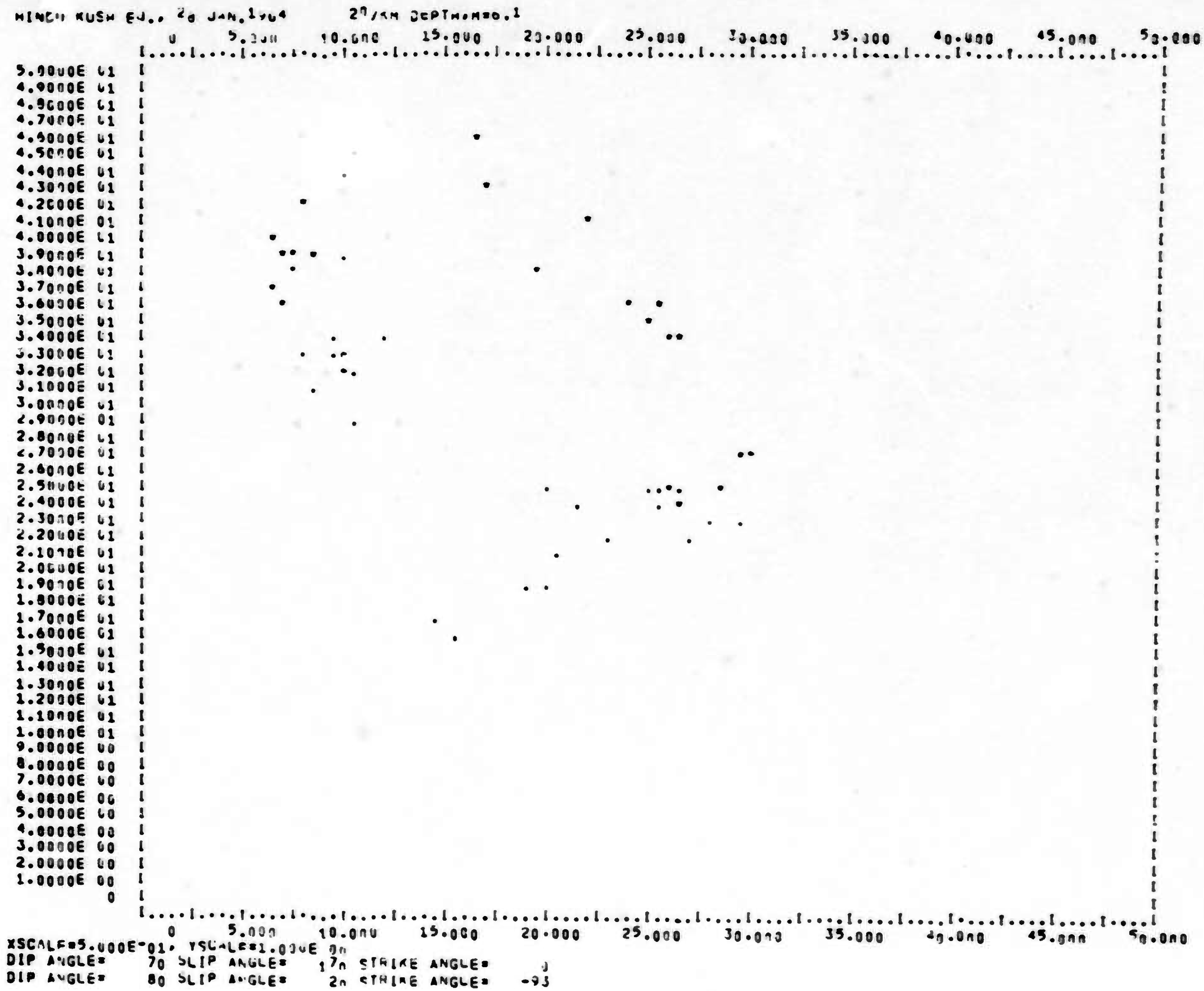


Figure 16. Calculated Radiation Pattern for the Hindu Kush Earthquake of 28 January 1964.

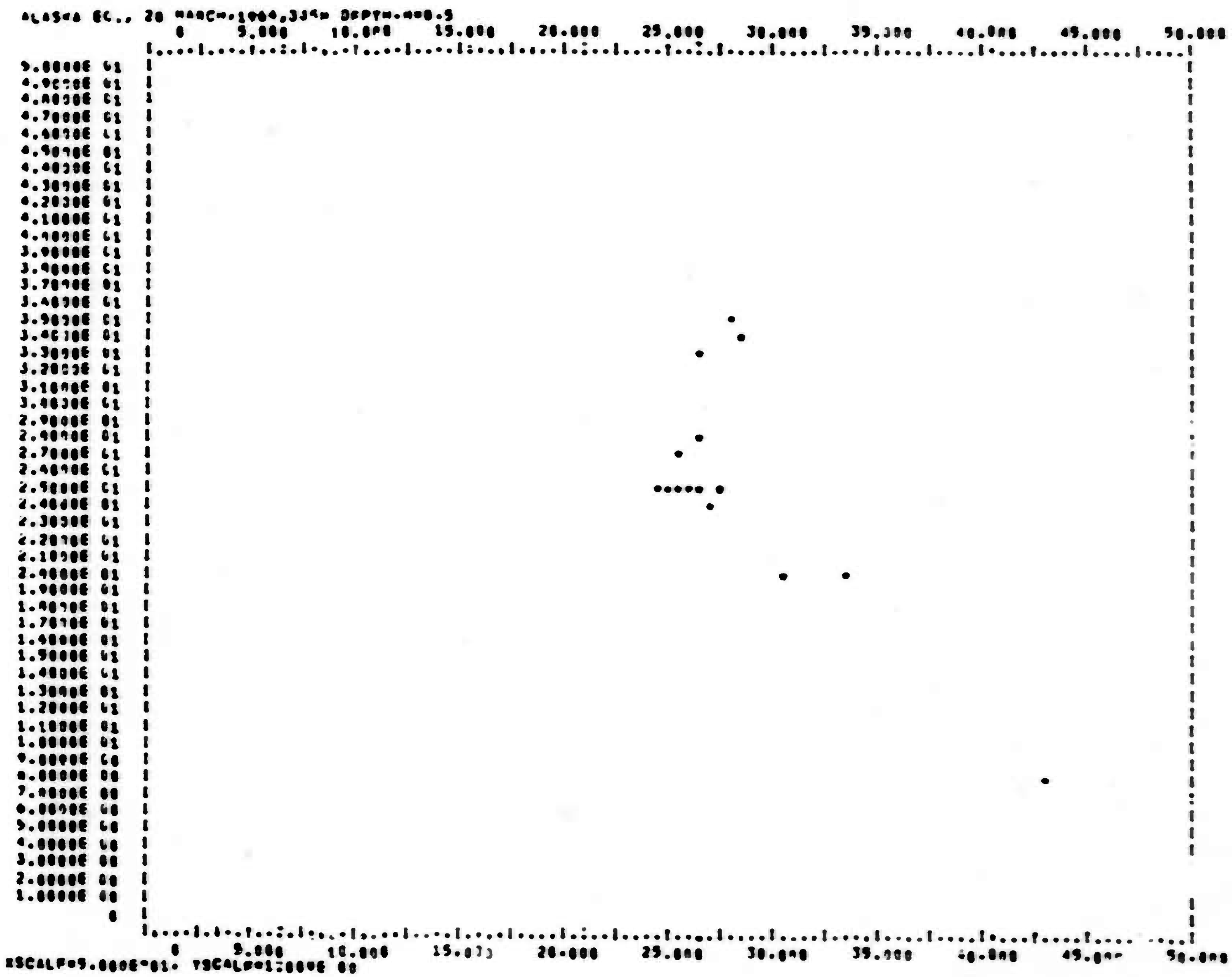


Figure 17. Observed Radiation Pattern for the Alaskan Earthquake of 28 March 1964.

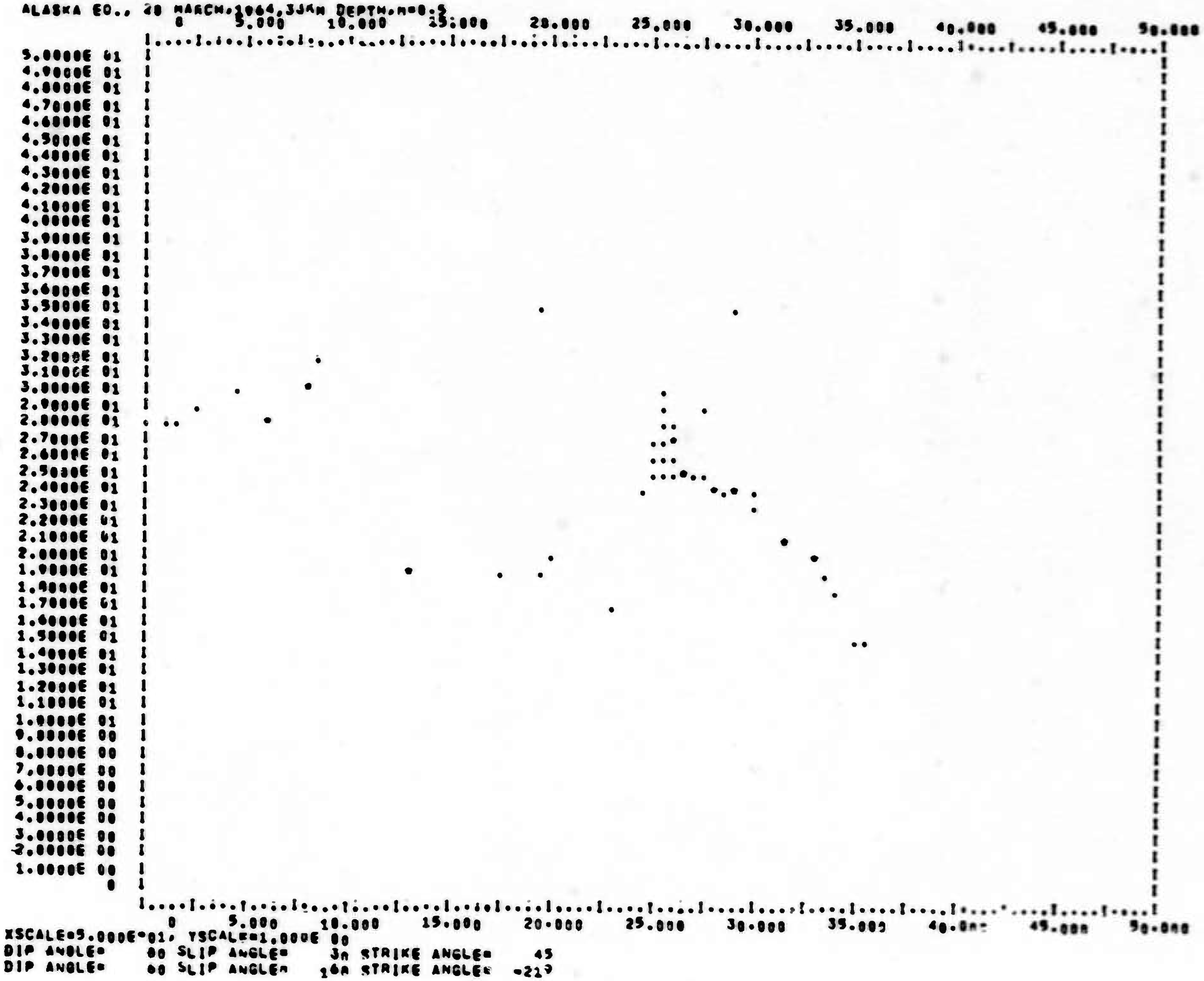


Figure 18. Calculated Radiation Pattern for the Alaskan Earthquake of 28 March 1964.

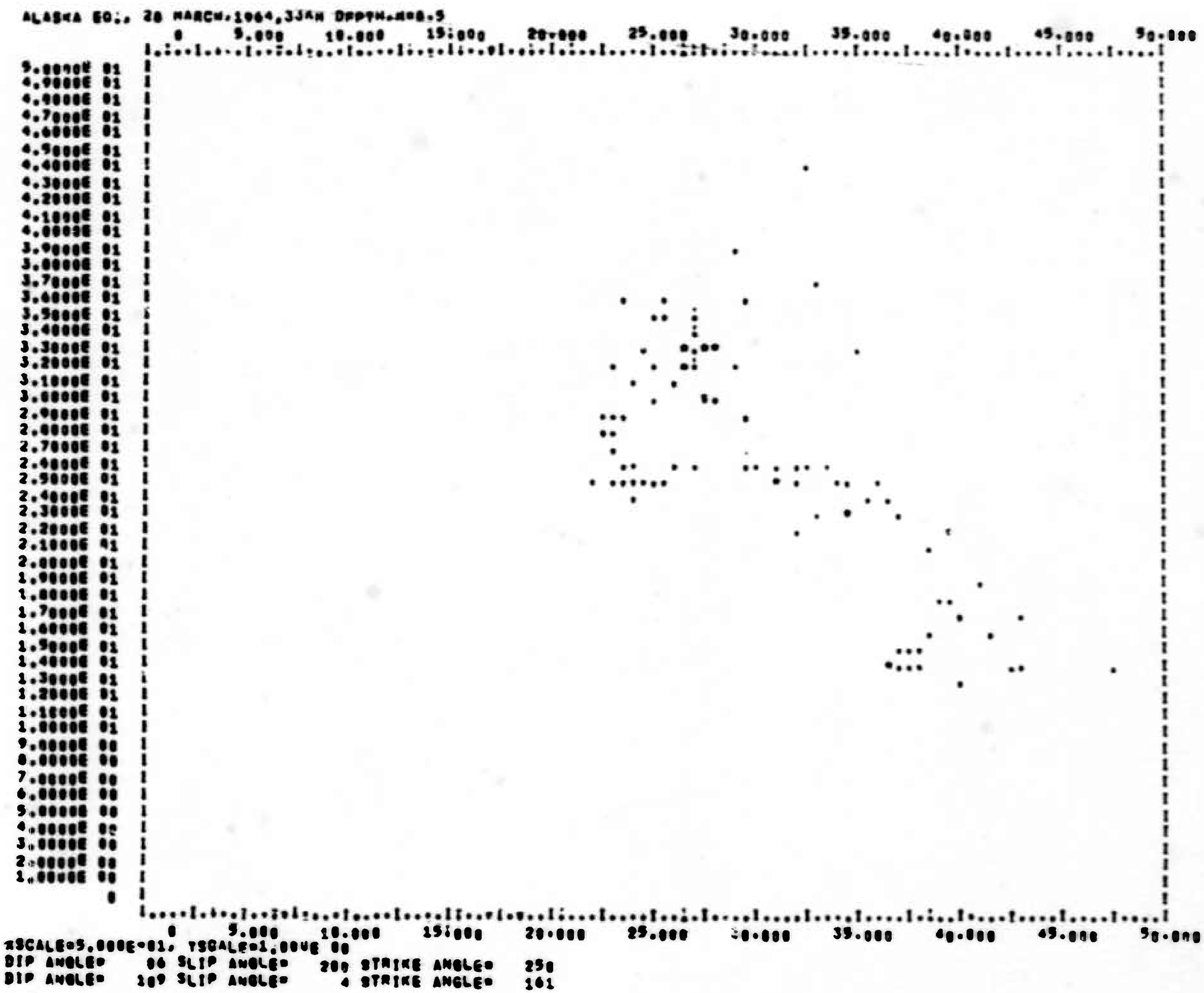


Figure 19. Calculated Radiation Pattern for the Alaskan Earthquake of 28 March 1964 (additional first motions).

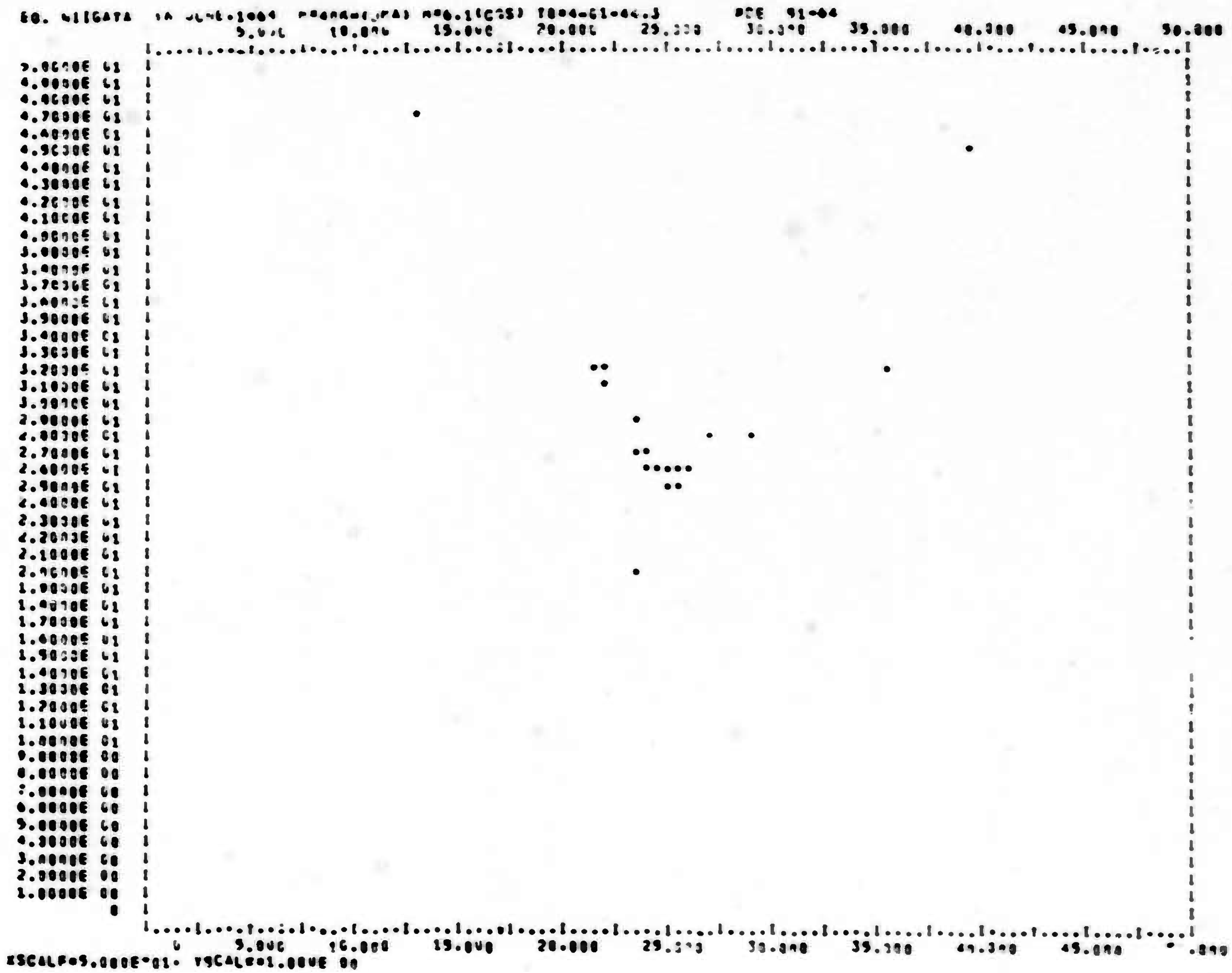


Figure 20. Observed Radiation Pattern for the Niigata Earthquake of 16 June 1964.

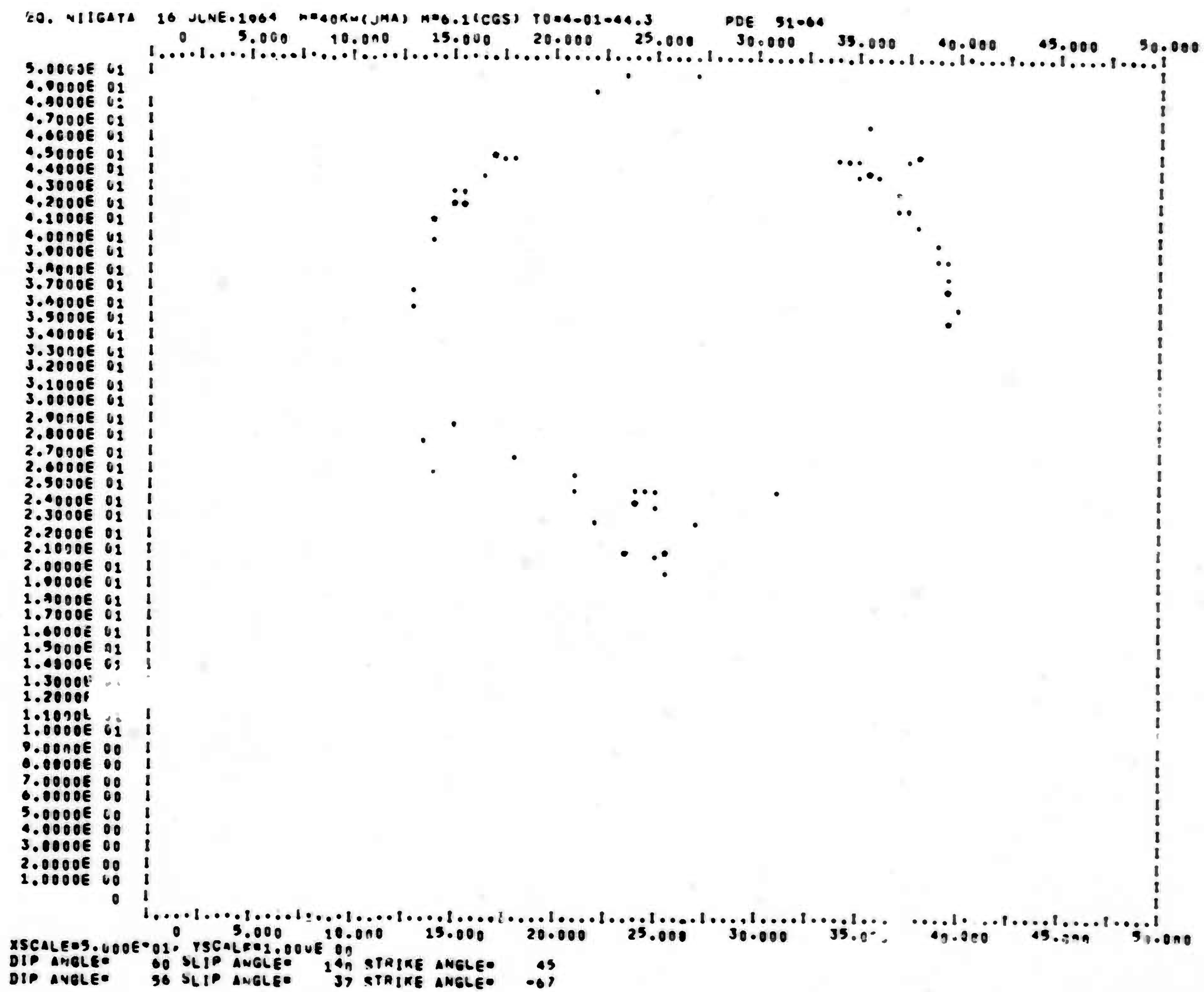


Figure 21. Calculated Radiation Pattern for the Niigata Earthquake of 16 June 1964.

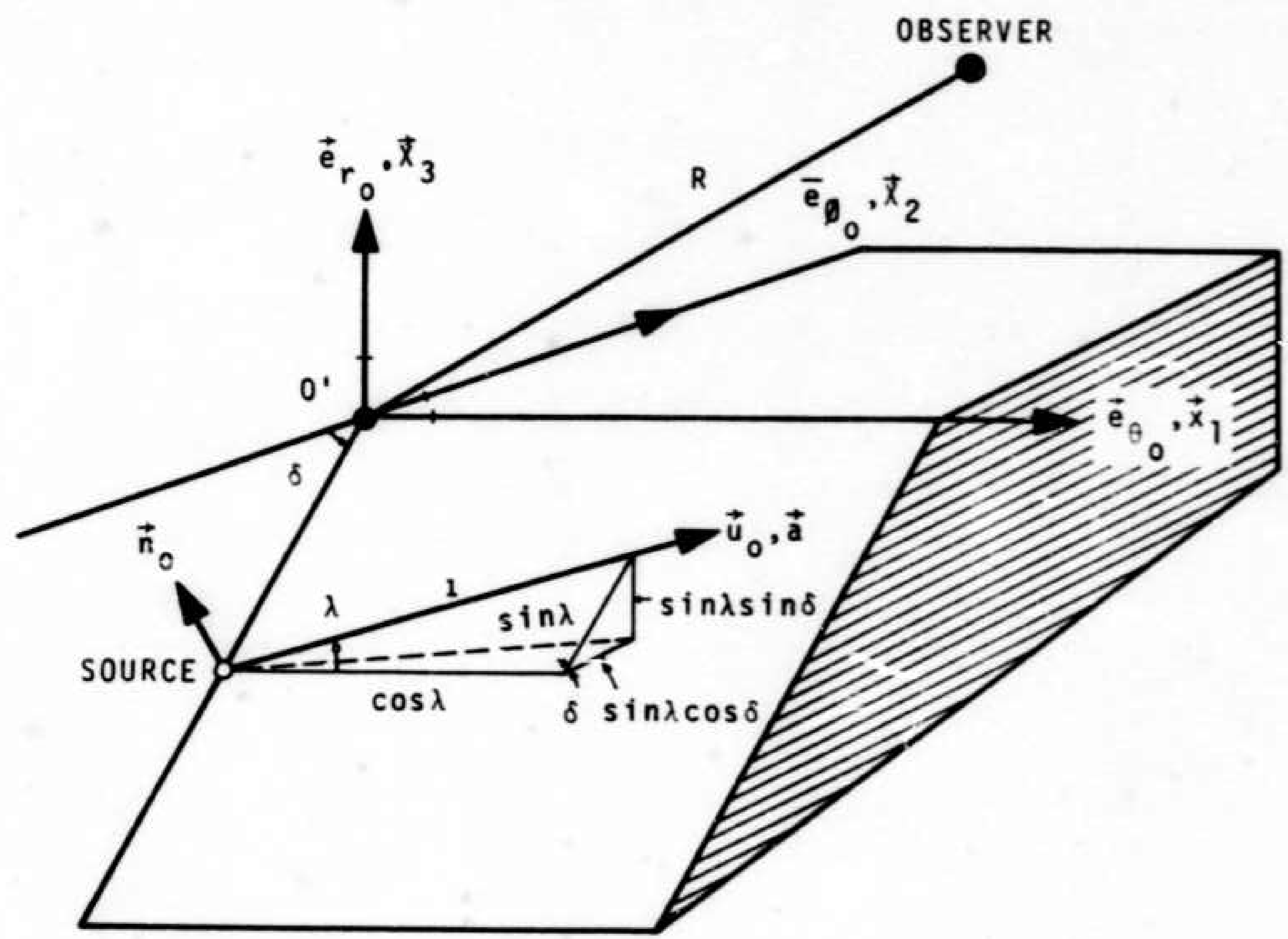


Figure 22. Geometry of a shear dislocation source

APPENDIX

Program RADPAT - Input Card Formats and Parameters

Part I (only read in once) Ritsema i - Δ table.

1st card

NTAB	Col. 1-5	Number of values in table (I5)

2nd and subsequent NTAB/4 cards (8F10.2)

ANG(I)	Col. 1-10	Δ° (F10.2)
XIO(I)	11-20	i_h° (F10.2)

Repeat for columns 21-40, 41-60, 61-80 as necessary

Part II (only read in once) - Gutenberg-Richter Distance-Depth Correction Table (for use with input values of $\log_{10}$ A/T).

108 cards, each has format (4X, 17F4.1), hence every card contains 17 fields, for a depth of 0(25)100, 150(50)700 kilometers.

Part III - Earthquake data

1st card

N	Col. 1-5	Number of earthquakes to be treated (I5)

2nd card

ID	Col. 1-80	Earthquake identification (10A8)

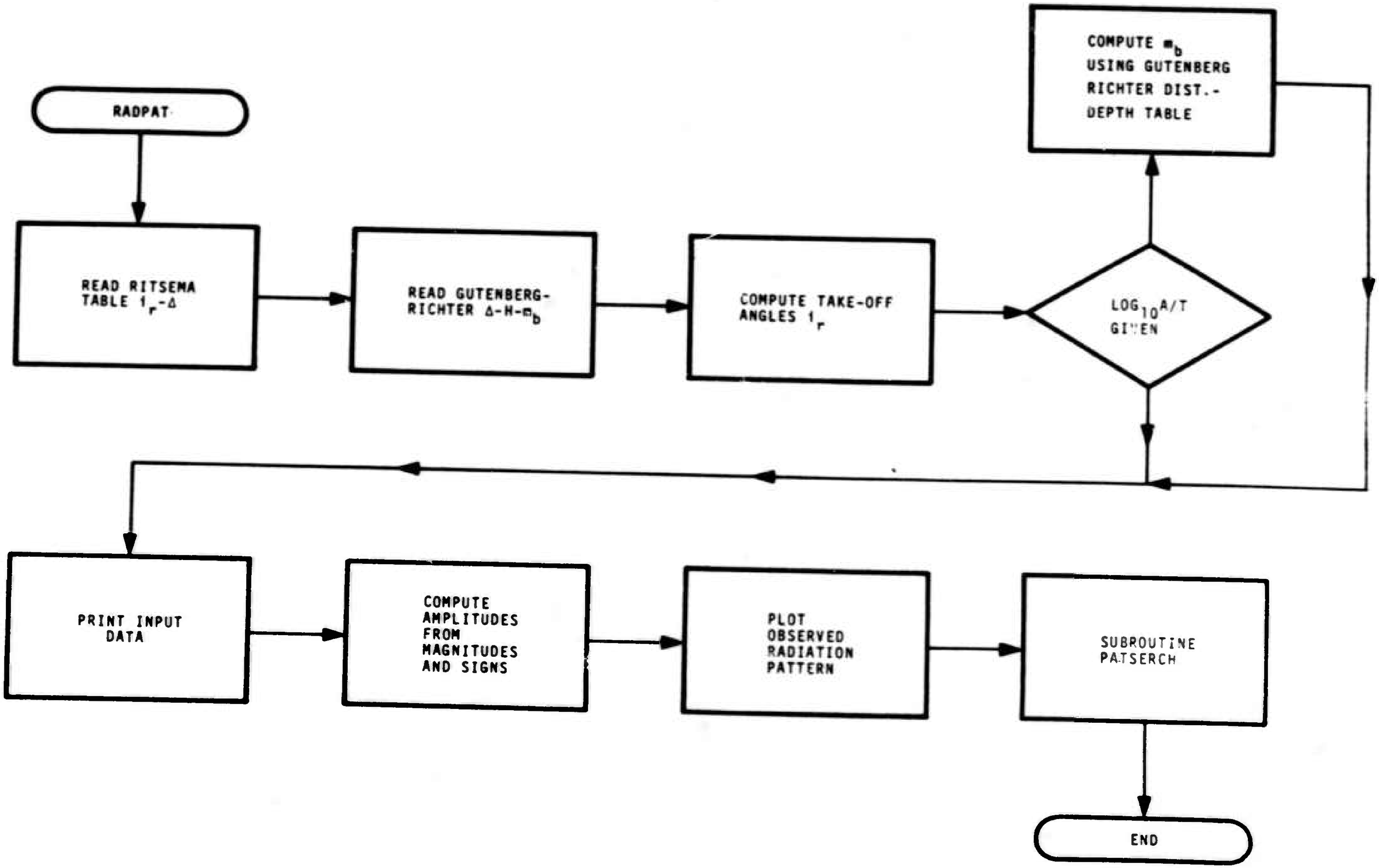
3rd card

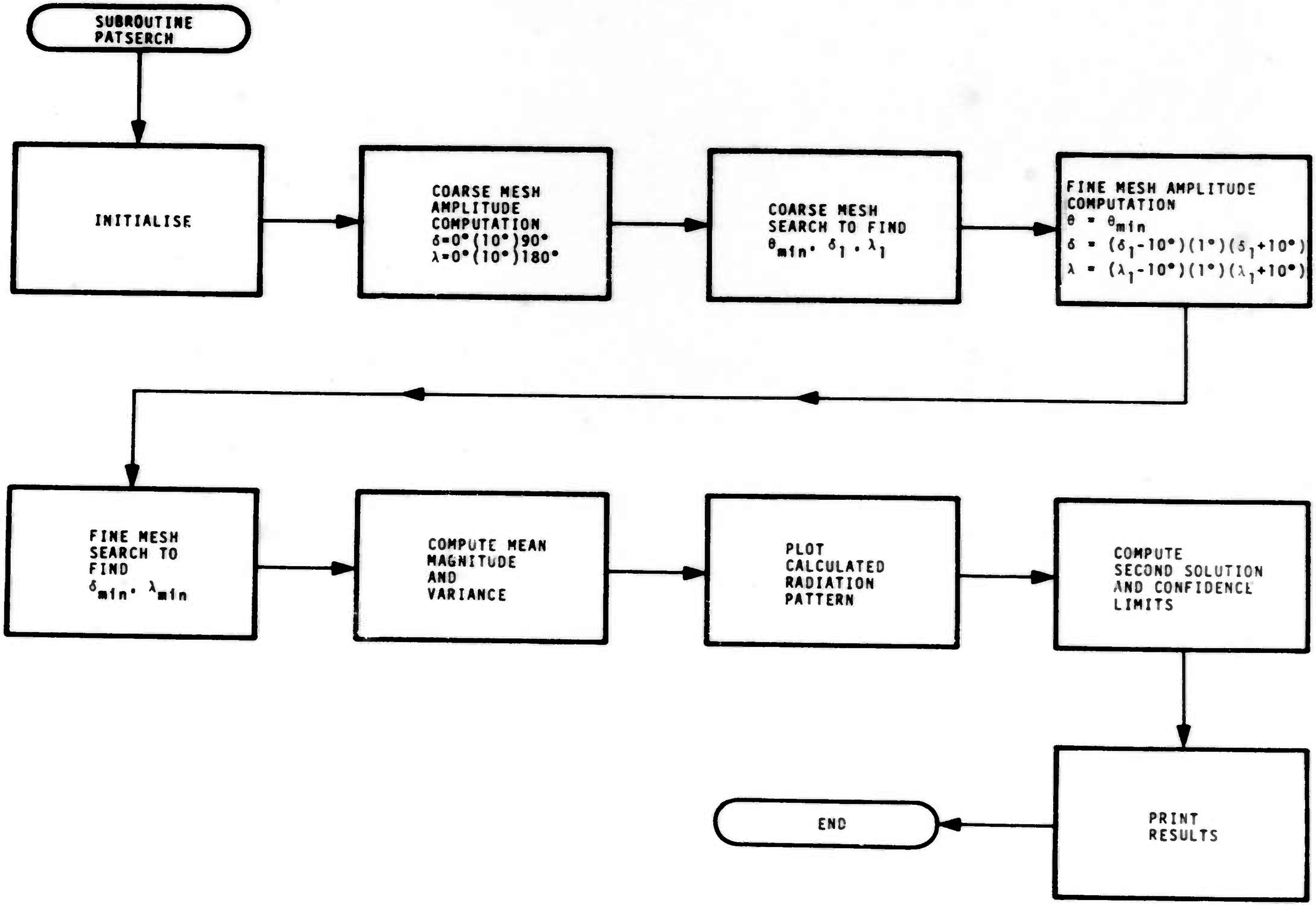
M	Col. 1-5	Number of stations (I5)	
ITAB	6-10	.LE.0	magnitudes are given as input (I5)
		.GT.0	$\log_{10}$A/T is input and the Gutenberg-Richter correction is to be applied.

DEPTH	11-20	Depth of the hypocenter (F10.1)
STRIKEO	21-30	Initial strike angle for the search (F10.1)
DELSTRI	31-40	Increment in strike angle (F10.1)
NSTRI	41-45	Number of increments to be used (I5)

Subsequent M cards contain the station data

STA(I)	1-5	Station identification (A5)
DIST(I)	11-20	Distance in degrees (F10.1)
THETA(I)	21-30	Azimuth-epicenter-to-station in degrees (F10.1)
MAG(I)	31-40	Magnitude or $\log_{10}$ (A/T) (F10.1)
ISIGN(I)	41-45	First motion direction (I5) -1 indicates dilatation 1 indicates compression 0 or blank - if unknown, will be taken as compression


RADPAT
READ RITSEMA TABLE i_r-Δ
READ GUTENBERG-RICHTER Δ-H-m_b
COMPUTE TAKE-OFF ANGLES i_r
$LOG_{10}A/T$ GIVEN
COMPUTE m_b USING GUTENBERG RICHTER DIST.-DEPTH TABLE
PRINT INPUT DATA
COMPUTE AMPLITUDES FROM MAGNITUDES AND SIGNS
PLOT OBSERVED RADIATION PATTERN
SUBROUTINE PATSERCH
END



SUBROUTINE PATSERCH
INITIALISE
COARSE MESH AMPLITUDE COMPUTATION δ=0°(10°)90° λ=0°(10°)180°
COARSE MESH SEARCH TO FIND θmin, δ1, λ1
FINE MESH AMPLITUDE COMPUTATION θ = θmin δ = (δ1-10°)(1°)(δ1+10°) λ = (λ1-10°)(1°)(λ1+10°)
FINE MESH SEARCH TO FIND δmin, λmin
COMPUTE MEAN MAGNITUDE AND VARIANCE
PLOT CALCULATED RADIATION PATTERN
COMPUTE SECOND SOLUTION AND CONFIDENCE LIMITS
PRINT RESULTS
END

Unclassified

Security Classification

DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

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Jarosch, H.S.,

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13. ABSTRACT

A new method is proposed for improving the body-wave magnitude determination by using the observed values of the body-wave magnitude (m_b) together with the first motion directions, to obtain by least squares analysis the best double couple source parameters; the resulting radiation pattern is then integrated spatially to provide a corrected estimate of the magnitude. Results for a number of events previously studied by other investigators are presented.

14. KEY WORDS

Body Wave Magnitude

Source Mechanism

Unclassified

Security Classification